

FAR-IR, SUBMM, & MM DETECTOR TECHNOLOGY WORKSHOP



Organized & Sponsored by NASA/Ames & USRA/SOFIA

1 - 3 April 2002

Monterey, California



Final Technical Program

Endorsed by: NASA Headquarters
German Aerospace Center, DLR

Release 1: March 27, 2002

PROGRAM OUTLINE

PURPOSE

The Far-IR, Submm & mm Detector Technology Workshop will provide a forum for the community of observers, instrument developers, detector developers, and the NASA IR Detector Working Group to discuss detector technology and development issues for wavelengths longer than 30 microns. The workshop would specifically:

- 1- Review present and future Far-IR, Sub-mm, and mm missions/science;
- 2- Outline the new technologies being explored by detector developers and their projections of the state-of-the-art technologies beyond 2010;
- 3- Outline the available infrastructure and needed new infrastructure required to develop and characterize new detector arrays and their electronics to supply foreseen science instrument/mission developments;
- 4- Identify possible future involvement by industry in detector development for wavelengths longer than 30 microns;
- 5- Provide input to the NASA IR/ Sub-mm Detector Working Group; and
- 6- Produce proceedings that will be a useful reference document for the community.

WORKSHOP SESSIONS

Introduction

- Opening remarks: Purpose of workshop
- Overviews on science and future missions in the FIR/Sub-mm/mm

Session 1: From the Decadal Report to Detector Requirement:

- Cosmic Microwave Background (SZ, Polarization, Secondary Anisotropy)
- Extra-Galactic (High Z Galaxies, Evolution, Structure Probes, Onset of Modern Universe)
- Galactic (Star formation, Galaxy Structure, Interstellar Matter)

Session 2: Photoconductor Detectors

- Advanced Arrays
- Theoretical Photoconductor Modeling
- Comparison of Modeled and Measured Behavior

Session 3: Poster Session: All topics

Session 4: Coherent Detection

- Front Ends
- Local Oscillators
- Backend Spectrometers

Session 5: Bolometer Systems

- Thermometers: NTD, Ion Implanted, TES
- Coupling Schemes
- Array Design
- Cold Multiplexing

Session 6: Promising Future Detector Technology

Summary and Discussion

ORGANIZERS

SCIENCE ORGANIZING COMMITTEE

Stephan Meyer (Chair)	<i>University of Chicago</i>
Sarah Church	<i>Stanford University</i>
Reinhard Genzel	<i>Max-Planck-Institut fuer Extraterrestrische Physik/UC Berkeley</i>
Eugene Haller	<i>UC, Berkeley/Lawrence Berkeley National Lab</i>
Thomas Henning	<i>Friedrich Schiller Universitaet, Jena</i>
William McGrath	<i>JPL</i>
Harvey Moseley	<i>NASA-Goddard</i>
Daniel Prober	<i>Yale University</i>
George Rieke	<i>University of Arizona</i>
Hans-Peter Röser	<i>DLR, Institut fuer Weltraumsensorik und Planetenerkundung, Berlin</i>
Charles Telesco	<i>University of Florida</i>
Jonas Zmuidzinas	<i>Caltech</i>

EX-OFFICIO SOC MEMBERS

Erick Young (Chair)	<i>University of Arizona</i>
Charles Lawrence	<i>JPL</i>
Craig McCreight	<i>NASA-Ames</i>
Paul Richards	<i>UC Berkeley</i>

LOCAL ORGANIZING COMMITTEE

Jackie Davidson (Chair)	<i>USRA-SOFIA</i>
Sean Casey	<i>USRA-SOFIA</i>
Jessie Dotson	<i>NASA-Ames</i>
Jam Farhoomand	<i>TechnoScience Corp. / NASA-Ames</i>
Craig McCreight	<i>NASA-Ames</i>
Jürgen Wolf	<i>DLR - SOFIA</i>

ADMINISTRATIVE ASSISTANTS

Lisa Frenette	<i>USRA-SOFIA</i>
Peggy Gross	<i>USRA-SOFIA</i>
Nancy Lee	<i>USRA-SOFIA</i>
Nancy McKown	<i>USRA-SOFIA</i>

SPONSORING ORGANIZATIONS

USRA-SOFIA
NASA-Ames Research Center

With endorsements from:

NASA Headquarters
German Aerospace Center, DLR

WORKSHOP SCHEDULE AT A GLANCE

MONDAY, APRIL 1		
Afternoon	2:00 PM	Workshop sign up
	4:30 PM	No-host bar
	5:30 PM	Dinner
Evening	7:00 PM	Introduction session starts
TUESDAY, APRIL 2		
Morning	7:00 AM	Breakfast
	8:00 AM	Session 1 starts. From the Decadal Report to Detector Requirement
	10:00 AM	Coffee break
	11:20 AM	Session 2 starts. Photoconductor Detectors
	12:00 PM	Lunch
Afternoon	1:30 PM	Session 2 resumes
	2:30 PM	Coffee break
	3:00 PM	Session 2 resumes
	4:30 PM	No-host bar / poster set up
	5:30 PM	Dinner
Evening	7:00 PM	Session 3 starts. Poster session
WEDNESDAY, APRIL 3		
Morning	7:00 AM	Breakfast
	8:00 AM	Session 4 starts. Coherent Detection
	10:20 AM	Coffee break
	11:00 AM	Session 5 starts. Bolometer Systems
	11:50 AM	Lunch
Afternoon	1:00 PM	Session 5 resumes
	3:50 PM	Coffee break
	4:20 PM	Session 6 starts. Promising Future Detector Technology
	6:45 PM	Dinner
Evening	8:00 PM	Summary and Discussion starts

DAILY SCHEDULE

2:00 PM **WORKSHOP SIGN UP**

4:30 PM **NO-HOST BAR**

5:30 PM **DINNER**

INTRODUCTION: OVERVIEW OF SCIENCE AND TECHNOLOGY		
Chair: Jackie Davidson (USRA/SOFIA)		
Monday, April 1		7:00 PM

7:00 PM	Opening Remarks <u>Jackie Davidson</u> (USRA/SOFIA)	
7:05 PM	Title to be announced <u>Scott Hubbard</u> (NASA-Ames)	
7:15 PM	Welcoming Remarks from USRA-SOFIA <u>Eric Becklin</u> (USRA/SOFIA)	
7:20 PM	Far-Infrared, Sub-mm, and mm Detectors: Looking Back and Looking Ahead , (invited) <u>Erick Young</u> (U of Arizona)	i-01
8:00 PM	Recommendations from the "Second Workshop on New Concepts for Far-IR/Submillimeter Space Astronomy" , (invited) <u>Dominic Benford</u> (NASA-Goddard)	i-02
8:20 PM	Infrared Space Astronomy in Germany , (invited) <u>Gernot Hartmann</u> (DLR, Germany)	i-03
8:40 PM	Future Missions Planned by Japan in the Far-IR, Sub-MM, & MM , (invited) <u>Shuji Matsuura</u> (ISAS, Japan)	i-04

SESSION 1: FROM THE DECADAL REPORT TO DETECTOR REQUIREMENT		
Chair: Stephan Meyer (University of Chicago)		
Tuesday, April 2		8:00 AM

8:00 AM	Future Detectors Needs for CMB Observations , (invited) <u>Andrew Lange</u> (CalTech)	1-01
9:00 AM	Prospects for High Resolution Spectroscopy from Future Space Platforms , (invited) <u>Tom Phillips</u> (CalTech)	1-02
10:00 AM	COFFEE BREAK	
10:20 AM	Detectors for the Future of Extra-Galactic Astrophysics , (invited) <u>Reinhard Genzel</u> (Max Planck/UC Berkeley)	1-03

SESSION 2: PHOTOCONDUCTOR DETECTORS

Chairs: Eugene E. Haller (UC Berkeley/LBNL) and
George Rieke (University of Arizona)

Tuesday, April 2

11:20 AM

- 11:20 AM **Experience with Space Photoconductive Detectors**, (invited)
George Rieke (U of Arizona) 2-01
- 12:00 PM **LUNCH**
- 1:30 PM **Stressed Ge:Ga Detector Arrays for PACS and FIFI LS**, (invited)
Dirk Rosenthal (Max-Planck-Institut fuer extraterrestrische Physik), J.W. Beeman (LBNL), N. Geis (MPE), U. Grözinger (MPIA), R.O. Katterloher (MPE), S. Kraft (ANTEC GmbH), L.W. Looney, A. Poglitsch, W. Raab (MPE), H. Richter (ANTEC GmbH) 2-02
- 2:00 PM **Current Status of the Detector Development for the Far-Infrared Surveyor (FIS) on ASTRO-F**, (invited)
Shuji Matsuura, Midori Akazaki, Yosuke Isozaki, Hidehiro Kaneda, Takao Nakagawa, Mihkael A. Patrashin, Mai Shirahata (ISAS, Japan), Mikio Fujiwara (CRL), Yasuo Doi (U of Tokyo), Yasunori Hibi, Takanori Hirao, Mitsunobu Kawada, Hirohisa Nagata, Hiroshi Shibai, Toyoki Watabe (Nagoya University), Manabu Noda (Nagoya City Science Museum) 2-03
- 2:30 PM **COFFEE BREAK**
- 3:00 PM **Numerical Modeling of Transient Behavior in Far-Infrared Photoconductors**, (invited)
Nancy Haegel (Fairfield University) 2-04
- 3:30 PM **Development of Advanced Photoconductor Arrays**, (invited)
Erick Young, George Rieke, James Davis (U of Arizona) 2-05
- 4:00 PM **Far Infrared Photoconductors: Recent Advances and Future Prospects**, (invited)
E.E. Haller (UC Berkeley/LBNL), J.W. Beeman (LBNL) 2-06
- 4:30 PM **NO-HOST BAR / POSTER SETUP**
- 5:30 PM **DINNER**

SESSION 3: POSTER SESSION

Chairs: Reinhard Genzel (Max Planck/UC Berkeley),
Harvey Moseley (NASA-Goddard), and
Hans-Peter Röser (DLR)

Tuesday, April 2

7:00 PM

- 7:00 PM **Introduction by the Session Chairs**
Reinhard Genzel (Max Planck/UC Berkeley), Harvey Moseley (NASA-Goddard), Hans-Peter Röser (DLR)

From the Decadal Report to Detector Requirement

Interstellar Magnetic Field Studies and Requisite Detector Properties

Dan Clemens (Boston University) 3-01

A Redshift Distribution of SCUBA Submm Galaxies through Keck Spectroscopy, and Modeling of the Population

Scott Chapman, I. Smail, A. Blain, R. Ivison (CalTech) 3-02

Optically Faint Counterparts to the ISO-FIRBACK 170Micron Population: the Discovery of Cold, Luminous Galaxies at High Redshift
Scott Chapman, G. Helou (CalTech) 3-03

Photoconductor Detectors

THUMPER - A 200-Micron Camera for the JCMT

Rhodri Evans, Derek Ward-Thompson, Peter Ade, Walter Gear, Matt Griffin, Sarah Leeks, Richard Walker (Cardiff University) 3-04

Initial Test Results of SBRC-190, a Multi-Gain, Cryogenic Readout Multiplexer for IR Detector Arrays

Jam Farhoomand, David Sisson, Lunming Yuen, Dzung Hoang (TechnoScience Corp./NASA-Ames) 3-05

The Development of a 30-125 Micron Array for Airborne Astronomy

Christopher Mason (SETI Institute), Jessie L. Dotson (NASA-Ames), Christopher T. Koerber (TechnoScience/NASA-Ames), Edwin F. Erickson, Michael R. Haas (NASA-Ames), Anita Prasad (TechnoScience Corp., currently at Intrinsix Technologies), Fred C. Witteborn (Orbital Sciences Corp.), Jam Farhoomand, David Sisson (TechnoScience/NASA-Ames) 3-06

Evaluation of Cryogenic Readout Electronics for ASTRO-F

Toyoki Watabe, Takanori Hirao, Hiroshi Shibai, Mitsunobu Kawada, Hiroshi Nagata, Yasunori Hibi, Manabu Noda (Nagoya University) 3-07

Transient Modeling and Measurements for Ge:Ga Photoconductors

William Schwartz, Matthew Smylie, Nancy M. Haegel (Fairfield University) 3-08

Far Infrared Photovoltage Effect in a Blocked Impurity Band Photodetector

Jean Leotin (Université Paul Sabatier, France), V.V. Rylkov, D.YU. Kovalev, B.A. Aronzon (Russian Research Center, Kurchatov Institute, Russia) 3-09

4.2K Multichannel Readout Circuitry in a Standard 0.7-Micron CMOS Process for a Photoconductor Array Camera

Ybe Creten, Patrick Merken, Jan Putzeys, Chris Van Hoof (IMEC, MCP division, Belgium) 3-10

Far-IR Calibration Sources for Cryogenic Focal Planes

Jeff Beeman (LBNL), Eugene E. Haller (UC Berkeley/LBNL) 3-11

High-Purity LPE GaAs for Far Infrared Blocked Impurity Band Detectors

Ben Cardozo (UC Berkeley/LBNL), Jeff Beeman (LBNL), Eugene E. Haller (UC Berkeley/LBNL) 3-12

Transient Effects of IR Photodetectors: the Lessons From ISO

Alain Coulais, Alain Abergel (CNRS/IAS, France) 3-13

Design Considerations for Large Format FIR Array Detectors

Juergen Wolf (DLR - USRA/SOFIA), Alan W. Hoffman (Raytheon Infrared Operations), Jeffrey W. Beeman (LBNL), Jam Farhoomand (TechnoScience Corp./NASA-Ames) 3-14

The SBRC-190: A Cryogenic Multiplexer for Moderate-Background FIR Astronomy

Edwin Erickson (NASA-Ames), Erick T. Young (Steward Observatory/U of Arizona), Juergen Wolf (DLR), James F. Asbrock, Nancy Lum (Raytheon IR Operations) 3-15

Germanium Blocked Impurity Band Detectors

Supriya Goyal (LBNL), Jordana Bandaru (JPL), Jeffrey W. Beeman (LBNL), Eugene E. Haller (UC Berkeley/LBNL) 3-16

Evaluation of Transient Behavior of Ge:Ga detectors for ASTRO-F

Hidehiro Kaneda, Midori Akazaki, Shuji Matsuura, Takao Nakagawa, Michail Patrashin, Yousuke Isozaki, Mai Shirahata (ISAS, Japan), Mikio Fujiwara (CRL), Yoshihiko Okamura (NASDA), Mitsunobu Kawada, Hiroshi Shibai, Takanori Hirao, Toyoki Watabe (Nagoya University)

3-17

Modeling of Growth Parameter Effects for Far Infrared Blocked Impurity Band Detectors

S.A. Samperi, N.M. Haegel (Fairfield University), A.M. White (White Numeric Consulting, England)

3-52

Coherent Detection

Advanced HEMT MMIC Circuits for Millimeter and Submillimeter-wave Power Sources

Lorene Samoska, Alejandro Peralta (JPL)

3-18

Optoelectronic Terahertz Sources Based on Photomixers

Pin Chen, Peter H. Siegel, Herbert M. Pickett, John C. Pearson (JPL), Rolf A. Wyss (JPL, currently at cQuint Communications), Andrea Neto (JPL, currently at FEL-TNO), Arthur C. Gossard (UCSB)

3-19

Tantalum Hot-Electron Bolometers for Heterodyne Receivers

Anders Skalare, William R. McGrath, Bruce Bumble, Henry G. LeDuc (JPL)

3-20

An Extremely Wide Bandwidth, Low Noise SIS Heterodyne Receiver Design for Millimeter and Submillimeter Observations

Matthew Sumner, Frank Rice (CalTech), Robert Hu (U of Michigan), Jonas Zmuidzinas (CalTech)

3-21

Diode-Laser Pumped Far-Infrared Local Oscillator Based on Semiconductor Quantum Wells

Cun-Zheng Ning, K. Kolokolov, J. Li, C.Z. Ning (NASA-Ames), D.C. Larrabee, J. Tang, G. Khodaparast, J. Kono (Rice University), S. Sasa, M. Inoue (Osaka Institute of Technology, Japan)

3-22

Integrated Terahertz Heterodyne Focal Plane Array Receivers

Gopal Narayanan, Neal Erickson (U of Mass)

3-23

Phonon Cooled Far-Infrared Hot Electron Bolometer Mixer

Heinz-Wilhelm Hübers, A. Semenov, H. Richter (DLR, Germany), K. Smirnov, G. Gol'tsman, B. Voronov (State Pedagogical University, Russia)

3-24

Micromechanical Waveguide Mounts for Hot Electron Bolometer Terahertz Mixers

Michael Brandt, Karl Jacobs, C.E. Honingh, Jörg Stodolka (U of Cologne, Germany)

3-25

Low Noise SIS Mixer for the Frequency above 1 THz

Alexander Karpov, D. Miller, J. Zmuidzinas (CalTech), J.A. Stern, B. Bumble, H.G. LeDuc (JPL)

3-26

Bolometer Systems

TES Detector Noise Limited Readout Using SQUID Multiplexers

J. Staguhr, D. Benford, J. Chervenak, S.H. Moseley, R. Shafer (NASA-Goddard), E. Grossman, K. Irwin, C. Reintsema (NIST)

3-27

SAMBA: Superconducting Antenna-coupled, Multi-frequency, Bolometric Array

Alexey Goldin (JPL), James J. Bock (JPL), Cynthia Hunt (CalTech), Andrew E. Lange (CalTech), Henry LeDuc (JPL), Anastasios Vayonakis (CalTech), Jonas Zmuidzinas (CalTech)

3-28

Absorber Coupled Transition-Edge-Sensor Bolometer Arrays for Submillimeter Imaging

James Chervenak, Johannes Staguhr, Dominic Benford, Rick Shafer, Harvey Moseley (NASA-Goddard)

3-29

SAFIRE: Far-Infrared Imaging Spectroscopy with SOFIA

S. Harvey Moseley, Dominic Benford, Jay Chervenak (NASA-Goddard), Kent Irwin (NIST), François Pajot (IAS), Rick Shafer (NASA-Goddard), Johannes Staguhr (NASA-Goddard/SSAI), Gordon Stacey (Cornell)

3-30

Thousand-Element Multiplexed Superconducting Bolometer Arrays

Dominic Benford, Jay Chervenak, George Voellmer (NASA-Goddard), Johannes Staguhn (NASA-Goddard/SSAI), Rick Shafer (NASA-Goddard), Gordon Stacey (Cornell), Kent Irwin (NIST) 3-31

Multiplexing Superconducting Bolometer Arrays

Rick Shafer (NASA-Goddard), Kent Irwin (NIST), Harvey Moseley (NASA-Goddard), Johannes Staguhn (NASA-Goddard/SSAI), Dominic Benford (NASA-Goddard), Ernie Buchanan (NASA-Goddard/SSAI), Umesh Patel (NASA-Goddard), Erich Grossman, Gene Hilton, Sae Woo Nam, Carl Reintsema (NIST), Piet de Korte (NIST/SRON), Joern Beyer (NIST/PTB Berlin) 3-32

Mission Requirements for Ultralow-background Large-format Bolometer Arrays

Dominic Benford, Harvey Moseley, Jay Chervenak (NASA-Goddard) 3-33

Single Pixel, Single Band Microstrip Antenna for Sub-Millimeter Wavelength Detection Using Transition Edge Superconducting Bolometric Receivers

Cynthia Hunt (CalTech), Jamie J. Bock, Peter K. Day, Alexey Goldin (JPL), Andrew E. Lange (CalTech), Henry G. LeDuc (JPL), Anastasios Vayonakis, Jonas Zmuidzinas (CalTech) 3-34

The Potential Benefits of Multimode Polarization and Frequency Selective Bolometers

John Ruhl (UCSB/Case Western Reserve University), Stephan Meyer (U of Chicago) 3-35

Hale, a Far-Infrared Polarimeter for SOFIA

Roger Hildebrand (U of Chicago), Jacqueline Davidson (USRA), Jessie Dotson (NASA-Ames), C. Darren Dowell (CalTech), Giles Novak (Northwestern University) 3-36

Development of High and Mid Tc Transition Edge Superconducting (TES) Bolometers on 1 to 5 μ m Thick Monolithic Sapphire Substrates for Space-Based Far IR Applications

Brook Lakew (NASA-Goddard), Shahid Aslam (Raytheon Corp.), John Brasunas (NASA) 3-37

Ideal Integrating Bolometer

Alan Kogut (NASA-Goddard) 3-38

Large-Format Planar Monolithic Bolometer Arrays for Far-Infrared and Submillimeter

Minoru Freund, D. Brent Mott, James P. Laughlin, Tina C. Chen, Alexander J. Bier, Barbara A. Campano, Rainer K. Fetting (NASA-Goddard) 3-39

Use of High Sensitivity Bolometers on Planck High Frequency Instrument

Michel Piat (Institut d'Astrophysique Spatiale), Jean-Michel Lamarre (IAS-LERMAPlanck-HFI Consortium) 3-40

Large Bolometer Arrays for the PACS/Herschel Instrument

Patrick Agnese (CEA/LETI/DOPT/SLIR, France), Louis Rodriguez, Laurent Vigroux (CEA/DSM/DAPNIA/ Service d'Astrophysique, France) 3-53

Cryocoolers for Space

Kittel Peter, Pat Roach, Jeff Feller (NASA-Ames), Ali Kashani, Ben Helvensteijn (Atlas Scientific) 3-54

Promising Future Detector Technology

GaAs LPE Growth Centrifuge - A Novel Facility to Produce High Purity GaAs Material

Reinhard Katterloher (Max Planck, Garching), Gerd Jakob (MPE, Germany), Mitsuharu Konuma (MPI-FKF, Germany), Nancy Haegel (Fairfield University), Eugene E. Haller (UC Berkeley/LBNL) 3-41

Submillimeter Wave Superconducting Hot-Electron Direct Detectors

Boris Karasik, Bertrand Delaet, William R. McGrath (JPL), Jian Wei, Michael E. Gershenson (Rutgers University), Andrew V. Sergeev (Wayne State University) 3-42

Design and Fabrication of a THz Nanoklystron

Harish Manohara, Peter H. Siegel, Colleen Marrese (JPL), Jimmy Xu, Baohe Chang (Brown University) 3-43

Detection of Terahertz Light with Intersubband Transitions in Semiconductor Quantum Wells

Carey Cates, B. Serapiglia, Y. Dora, J. Heyman, J.B. Williams, M.S. Sherwin (Physics Dept., UC Santa Barbara), K. Campman, K.D. Maranowski, A.C. Gossard (Materials Dept., UC Santa Barbara), W.R. McGrath (JPL) 3-44

Transferred Substrate Heterojunction Bipolar Transistors for Millimeter and Submillimeter Wave Applications

Andy Fung, Lorene Samoska, Peter Siegel (JPL) 3-45

The Millimeter-Wave Properties of Superconducting Microstrip Lines

Anastasios Vayonakis (CalTech), C. Luo (MIT), H.G. Leduc (JPL), R. Schoelkopf (Yale University), J. Zmuidzinas (CalTech) 3-46

WaFIRS, a Waveguide Far-IR Spectrometer for Space-Borne Astrophysics

C. Matt Bradford (CalTech), James Bock (JPL), Lieko Earle, Jason Glenn (CASA, U of Colorado), Bret Naylor (CalTech), Hien Nguyen (JPL), Jonas Zmuidzinas (CalTech) 3-47

Lead Telluride-Based Photodetectors - A Promising Alternative to Doped Si and Ge

Dmitriy Khokhloy, Dmitriy Dolzhenko, Ivan Ivanchik, Konstantin Kristovskiy (Moscow State University), Dan Watson, Judy Pipher (U of Rochester), Juergen Wolf (German Aerospace Center - DLR) 3-48

Background Limited Superconducting Quantum Detector for Astronomy

Alexei Semenov, Heinz-Wilhelm Hübers, Andreas Engel, Gregory N. Gol'tsman (DLR, Germany) 3-49

Limits to Efficiency of Imaging Systems

S. Harvey Moseley, Edward J. Wollack, Gary F. Hinshaw (NASA-Goddard) 3-50

Resonant Terahertz Photoconductance of Grating Gated Double Quantum Well Field Effect Transistors

Xomalin Peralta, S.J. Allen (iQUEST, UC Santa Barbara), M.C. Wanke, N.E. Harff, J.A. Simmons, M.P. Lilly, J.L. Reno, W.E. Baca (Sandia National Laboratories), P.J. Burke, J.P. Eisenstein (CalTech) 3-51

SESSION 4: COHERENT DETECTION

Chairs: William R. McGrath (JPL) and
Jonas Zmuidzinas (CalTech)

Wednesday, April 3

8:00 AM

8:00 AM **Coherent Detection and SIS Mixers**, (invited)

Jonas Zmuidzinas, Alexandre Karpov, David Miller, F. Rice (CalTech), Henry G. LeDuc, John Pearson, Jeffrey A. Stern (JPL) 4-01

8:25 AM **Superconductive Hot Electron Bolometer Mixers**, (invited)

William R. McGrath, Boris Karasik, Anders Sklare (JPL), Irfan Siddiqi, Daniel Prober (Yale) 4-02

8:50 AM **THz Local Oscillator Sources**, (invited)

Imran Mehdi, Erich Schlecht, Goutam Chattopadhyay, Peter H. Siegel (JPL) 4-03

9:15 AM **Spectrometers for Heterodyne Detection**, (invited)

Andrew Harris (U of Maryland) 4-04

9:40 AM **Amplifier Technology for Astrophysics**, (invited)

Todd Gaier, Sander Weinreb, Mary Wells, Charles Lawrence, Douglas Dawson (JPL), Richard Lai, Ronald Grundbacher, Roger Tsai, Augusto Gutierrez, Barry Allen (TRW) 4-05

10:00 AM **Techniques for Heterodyne Array Receivers**

David Rabanus, Urs U. Graf, Stefan Heyminck, Carl Jacobs, Rudolf Schieder, Stephan Stanko, Juergen Stutzki (U of Cologne, Germany) 4-06

10:20 AM **COFFEE BREAK**

SESSION 5: BOLOMETER SYSTEMS		
Chairs: Stephan Meyer (University of Chicago) and Paul Richards (UC Berkeley)		
Wednesday, April 3		11:00 AM
11:00 AM	Bolometric Detectors for Space Astrophysics , (invited) <u>Paul Richards</u> (UC Berkeley)	5-01
11:50 AM	LUNCH	
1:00 PM	Antenna-Coupled Bolometer Arrays for Astrophysics , (invited) <u>James Bock</u> (JPL)	5-02
1:30 PM	Large Format Bolometer Arrays for Far Infrared, Submillimeter, and Millimeter Wavelength Astronomy , (invited) <u>Harvey Moseley</u> (NASA-Goddard)	5-03
2:00 PM	Voltage-Biased Superconducting TES Bolometers for the Far-Infrared to Millimeter Wavelength Range , (invited) <u>Adrian Lee</u> , Sherry Cho, Jan M. Gildemeister, Nils Halverson, William Holzapfel, Jared Mehl, Mike Myers, Trevor Lanting, Paul L. Richards, Eva Rittweger, Dan Schwan, Jesse Skidmore, Jongsoo Yoon (UC Berkeley)	5-04
2:30 PM	SQUID-Based Multiplexers for Transition Edge Sensor Readout , (invited) <u>Mikko Kiviranta</u> , Heikki Seppä (VTT Microsensing, Finland), Jan van der Kuur, Piet de Korte (SRON, Netherlands)	5-05
2:50 PM	Frequency-Domain Multiplexing for Large-Scale Bolometer Arrays , (invited) <u>Helmuth Spieler</u> (LBNL)	5-06
3:10 PM	Fundamental Performance Limits of Time Division SQUID Multiplexers , (invited) <u>Kent Irwin</u> (NIST), Damian Audley (UK ATC), James Beall (NIST), Dominic Benford (NASA-Goddard), Joern Beyer (PTB, Berlin), Steve Deiker (NIST), Piet DeKorte (SRON, Netherlands), William Duncan (UK ATC), Gene Hilton (NIST), Wayne Holland (UK ATC), Michael MacIntosh (UK ATC), S. Harvey Moseley (NASA-Goddard), Sae Woo Nam (NIST), Carl Reintsema (NIST), Rick Shafer (NASA-Goddard), Johannes Staguhn (NASA-Goddard), Leila Vale (NIST)	5-07
3:30 PM	The SHARC II 350-Micron Bolometer Array: 384 Pixels Read in "Total Power" Mode <u>Charles Dowell</u> (CalTech), Christine A. Allen, S. Harvey Moseley (NASA-Goddard), Thomas G. Phillips (CalTech), George Voellmer (NASA-Goddard)	5-08
3:50 PM	COFFEE BREAK	

SESSION 6: PROMISING FUTURE DETECTOR TECHNOLOGY		
Chair: Sara Church (Stanford University) and Daniel Prober (Yale University)		
Wednesday, April 3		4:20 PM
4:20 PM	Integrated, Heterodyne Array Receivers for FIR Spectroscopy <u>Christopher Walker</u> (U of Arizona), Daniel Prober (Yale), Jacob Kooi (CalTech), Arthur Lichtenberger (U of Virginia), Gordon Chin (NASA-Goddard), Christian Drouet d'Aubigny, Christopher Groppi, Craig Kulesa, Abigail Hedden, Dathon Golish (U of Arizona)	6-01

- 4:40 PM **Multiplexable Kinetic Inductance Detectors**
Jonas Zmuidzinas (CalTech), P. Day, H.G. LeDuc (JPL), B. Mazin, A. Vayonakis (CalTech) 6-02
- 5:00 PM **Intersubband Terahertz Detectors**
Mark Sherwin, C. Cates, G. B. Serapiglia, Y. Dora, M. Hanson, A.C. Gossard (UCSB), W. R. McGrath (JPL) 6-03
- 5:20 PM **Antenna-Coupled Superconducting Tunnel Junctions with Single-Electron Transistor Readout for Detection of Sub-Mm Radiation**
Thomas Stevenson, W.T. Hsieh, M.J. Li, C.M. Stahle, E.J. Wollack (NASA-Goddard), R.J. Schoelkopf, J. Tuefel (Yale University) 6-04
- 5:40 PM **Development of Microshutter Arrays for the Near Infrared Spectrometer on NGST**
Robert Silverberg (LASP/ NASA-Goddard), S. Aslam, K.A. Blumenstock (NASA-Goddard), R.K. Fetting, D.E. Franz (RITSS/NASA-Goddard), M. Harvey (NASA-Goddard), A.S. Kutyrev (SSAI/NASA-Goddard), J. Laughlin, M.J. Li, S.H. Moseley, D.B. Mott (NASA-Goddard), D.A. Rapchun (GST/NASA-Goddard), D.S. Schwinger, S. Manthripragada, R.P. Wesenberg, Y. Zheng (NASA-Goddard) 6-05
- 6:00 PM **GaAs/AlGaAs Multi-Quantum-Well Based Far Infrared (> 30 Microns) Detectors for Astronomy Application**
Sumith Bandara, S.D. Gunapala, D.Z. Ting, S.B. Rafol, J.K. Liu (JPL) 6-06
- 6:20 PM **Far-Infrared Focal Plane Arrays**
A.L. Betz, R.T. Boreiko (U of Colorado), S. Sivananthan, Y.D. Zhou (U of Illinois-Chicago) 6-07
- 6:45 PM **DINNER**

SUMMARY AND DISCUSSION

Moderating Panel: Erick Young, chair (University of Arizona),
Charles Lawrence (JPL),
Craig McCreight (NASA-Ames), and
Paul Richards (UC Berkeley)

Wednesday, April 3

8:00 PM

ABSTRACTS

Introduction: Overview of Science and Technology

- (i-01) **Far-Infrared, Sub-mm, and mm Detectors: Looking Back and Looking Ahead**, (invited)
Erick Young (U of Arizona)

I give a brief history of the spectacular progress made in far-infrared, sub-millimeter, and millimeter detectors, largely through the efforts of the space astronomy community. I consider the large amount of work still needed to approach the needs of future missions. I describe the work of IR/Sub-mm Detector Working Group, whose charge is to recommend a technology development roadmap to NASA.

- (i-02) **Recommendations from the "Second Workshop on New Concepts for Far-IR/Submillimeter Space Astronomy"**, (invited)
Dominic Benford (NASA-Goddard)

The "Second Workshop on New Concepts for Far-Infrared/Submillimeter Space Astronomy" was a forum for community input into the NASA Space Science strategic planning process. The participants discussed science goals, mission concepts, and enabling technologies for future space observatories that will operate in the 20 - 800 micron wavelength range. The Workshop was held in Maryland March 7 - 8, 2002. It was motivated by the Decade Report's assignment of priority to a Single-Aperture Far-IR (SAFIR) telescope and encouragement of the subsequent development of space-based far-infrared interferometry. A white paper, currently in preparation, will give the community's recommended science and technology roadmap for space missions in the post-SIRTF, SOFIA, and Herschel era. The roadmap is intended to guide the implementation of the Decade Report recommendations. In this talk we will present a preview of the white paper.

- (i-03) **Infrared Space Astronomy in Germany**, (invited)
Gernot Hartmann (DLR, Germany)

After an introduction to the principle goals of the German Space Science program, the description of the community competence and the elements of the program participation both in ESA and in international cooperation, an overview will be given on the German role in infrared to mm astronomy airborne and space observatories. In particular, the German instrument contributions to the large projects ISO, SOFIA, Herschel and Planck will be briefly described. The areas and institutions of special experience will be outlined, demonstrating the strong German role in this field of astronomy.

- (i-04) **Future Missions Planned by Japan in the Far-IR, Sub-MM, & MM**, (invited)
Shuji Matsuura (ISAS, Japan)

We will describe two Japanese missions for far-infrared and sub-millimeter astronomy. One is ASTRO-F, which is a survey type mission with a 70-cm telescope and is scheduled for launch in early 2004. The other is SPICA (Space Infrared Telescope for Cosmology and Astrophysics), which is an observatory-type mission with a 3.5-m telescope. The target launch year for SPICA is 2010. We will also introduce some other proposed future Japanese missions, which are in the preliminary study phase

Session 1: From the Decadal Report to Detector Requirement

- (1-01) **Future Detectors Needs for CMB Observations**, (invited)
Andrew Lange (CalTech)

Observations of the Cosmic Microwave Background require highly specialized instrumentation and detector systems. I will summarize the detector requirements for this rapidly growing field, with an emphasis on the types of detectors that will be needed for high-resolution imaging and for polarimetry.

- (1-02) **Prospects for High Resolution Spectroscopy from Future Space Platforms**, (invited)
Tom Phillips (CalTech)

High spectral resolution is necessary in many astrophysical situations, usually requiring heterodyne devices. Some aspects of the role of these instruments will be discussed for the case of a large aperture telescope and for interferometers in space, with applications to molecular and atomic fine-structure spectroscopy.

- (1-03) **Detectors for the Future of Extra-Galactic Astrophysics**, (invited)
Reinhard Genzel (Max Planck/UC Berkeley)

High sensitivity measurements in the far-infrared and sub-millimeter spectral regions will play a central role in future progress in understanding the extra-galactic universe – in particular the high redshift universe. I will outline the steps needed to develop the detectors required for the next generation of missions which will provide these measurements.

Session 2: Photoconductor Detectors

(2-01) **Experience with Space Photoconductive Detectors**, (invited)

George Rieke (U of Arizona)

Far infrared photoconductors have systems-level advantages that have made them favored for many space astronomy missions. I will describe the current status of far infrared photoconductor arrays, particularly of those that have been developed for SIRTf. At the same time, this detector type has exhibited a number of challenges in providing well calibrated data. I will also discuss the variety of steps taken in the SIRTf application both in the instrument design and operations and in characterization and calibration efforts, to solve these problems.

(2-02) **Stressed Ge:Ga Detector Arrays for PACS and FIFI LS**, (invited)

Dirk Rosenthal (Max-Planck-Institut fuer extraterrestrische Physik), J.W. Beeman (LBNL), N. Geis (MPE), U. Grözinger (MPIA), R.O. Katterloher (MPE), S. Kraft (ANTEC GmbH), L.W. Looney, A. Poglitsch, W. Raab (MPE), H. Richter (ANTEC GmbH)

Gallium doped germanium detector arrays in a 16x25 pixel configuration will be used on two future instruments: In the spectrometer section of the Photodetector Array Camera and Spectrometer (PACS) aboard the Herschel satellite and the Field Imaging Far Infrared Line Spectrometer (FIFI LS) aboard the Stratospheric Observatory for Infrared Astronomy (SOFIA). Arrays of slightly stressed Ge:Ga detectors cover a wavelength range from 55 to 105 micron for PACS and from 40 to 120 micron for FIFI LS, whereas arrays of highly stressed Ge:Ga detectors cover a wavelength range from 105 to 210 micron for PACS and 120 to 210 micron for FIFI LS. The entire arrays consist of 25 independent modules of 16 pixels. The detector arrays will be operated with multiplexed integrating amplifiers with cryogenic readout electronics located close to the detector modules. The design of the detector arrays and results of first performance measurements will be reported.

(2-03) **Current Status of the Detector Development for the Far-Infrared Surveyor (FIS) on ASTRO-F**, (invited)

Shuji Matsuura, Midori Akazaki, Yosuke Isozaki, Hidehiro Kaneda, Takao Nakagawa, Mihkael A. Patrashin, Mai Shirahata (ISAS, Japan), Mikio Fujiwara (CRL), Yasuo Doi (U of Tokyo), Yasunori Hibi, Takanori Hirao, Mitsunobu Kawada, Hirohisa Nagata, Hiroshi Shibai, Toyoki Watabe (Nagoya University), Manabu Noda (Nagoya City Science Museum)

ASTRO-F is a Japanese infrared satellite, which is scheduled for launch in early 2004. Far-infrared instrument that will be onboard the ASTRO-F, Far-Infrared Surveyor (FIS), will provide the four-color all sky survey data in the 50-200 micron wavelength range with the diffraction-limited spatial resolution for the 70-cm diameter telescope. Owing to high performance of the readout circuit and to high spatial resolution to minimize the source confusion, the point source detection limit of the FIS should be more than an order of magnitude better than that of IRAS. The world's first monolithic Ge:Ga 20x3 array directly attached to the cooled readout circuit is used for the two short wave bands of 50-70 μ m and 50-110 μ m. A stressed Ge:Ga array with a novel assembling structure, which is built by stacking 20 pieces of 5-segment discrete array with light cavity, covers the long wave bands of 100-200 μ m and 150-200 μ m. The cooled readout circuit for both short and long wave arrays consists of Capacitive Trans-Impedance Amplifier (CTIA) composed of specially-made p-MOSFETs for low-temperature use. We will present the current development status of the FIS instruments, showing specific properties of the FIS detector and the readout circuit. We will also state future prospect of the advance in detector technology in Japan related to future space astronomy missions.

(2-04) **Numerical Modeling of Transient Behavior in Far-Infrared Photoconductors**, (invited)

Nancy Haegel (Fairfield University)

The transient response of extrinsic photoconductors can be modeled using a finite difference approach which includes all current components (drift, diffusion and displacement) and removes the need for

regional approximations. In this talk, recent progress in the numerical modeling will be reviewed, including the response to a wide range of modulated inputs and the role of non-uniform illumination in the transverse geometry. Non-uniform illumination has been shown to play a significant role in the origin of the hook response in Ge:Ga photoconductors. The modeling results suggest possible changes in fabrication and/or operation of extrinsic photoconductors that would minimize the difficulties in the interpretation and calibration of transient response.

(2-05) Development of Advanced Photoconductor Arrays, (invited)

Erick Young, George Rieke, James Davis (U of Arizona)

Photoconductor array detectors have been the detector of choice for a number of space far- infrared missions. Their combination of sensitivity, relaxed cooling requirements, and ease of fabrication have made photoconductors very useful for astronomical applications. We discuss the design considerations for arrays in the far infrared, and we describe the development of the large format germanium photoconductor array that will soon fly on the Space Infrared Telescope Facility. This capability will provide the first true imaging array at these wavelengths. We also discuss the extension of this technology to much larger formats and to a wide range of backgrounds. We also discuss recent efforts to improve the photometric calibration of these devices.

(2-06) Far Infrared Photoconductors: Recent Advances and Future Prospects, (invited)

E.E. Haller (UC Berkeley/LBNL), J.W. Beeman (LBNL)

The first germanium blocked impurity band (BIB) detectors displaying simultaneously all the properties characteristic for this type of photoconductive device have just been reported (1). Using a combination of bulk grown ultra-pure germanium and liquid phase epitaxy to form the required thin blocking layer on doped absorber layer structure, Ge BIB devices with a long wavelength cut-on near 50 cm^{-1} ($> 200\text{ }\mu\text{m}$) and low dark currents have been fabricated. Excessive diffusion of the majority donor dopant antimony results in a small depletion layer and low responsivity. These preliminary Ge BIB results are encouraging and they point the way for further improvements. Two approaches appear feasible: i.) LPE growth starting at lower temperatures reducing the Sb diffusion or ii.) improving the purity of the Pb solvent used in the LPE process to make possible the epitaxial growth of both the blocking and the absorber layer. The move to wavelengths beyond Ge BIB detectors will become possible with n-type GaAs BIB devices. With donor binding energies near 6 meV, such BIB detectors will show an onset beyond 30 cm^{-1} ($> 330\text{ }\mu\text{m}$). Successful growth of ultra-pure epitaxial layers has been demonstrated and can be achieved routinely in our laboratories using LPE with a liquid Ga solvent. The next step is the growth of appropriately doped n-type GaAs for the infrared active layer. We plan to use Te donors for this purpose because of their low diffusivity and large solubility limit. Looking beyond GaAs BIB detectors, an obvious candidate for the next generation of semiconductor photoconductors is InAs. This narrow band gap material has a donor binding energy of $\sim 3\text{ meV}$. Extrapolating from the Si, Ge and GaAs BIB detector long wavelength response limits, we expect InAs BIB detectors to show response out to less than 14 cm^{-1} ($> 700\text{ }\mu\text{m}$). Formidable materials problems need to be solved before InAs BIB array development becomes feasible but the promise of a photoconductor responding well into the wavelength range covered by bolometric detectors is highly attractive.

Session 3: Poster Session

(3-01) **Interstellar Magnetic Field Studies and Requisite Detector Properties**

Dan Clemens (Boston University)

Magnetic fields play important roles in cloud, cluster, and star formation. Yet magnetic fields are exceedingly difficult to detect and trace. The current best method involves measuring far-infrared linear polarization of aligned, spinning, thermal dust grains. SOFIA instruments and Small Explorer (SMEX) missions have been proposed that would routinely measure interstellar magnetic fields. But, these instruments and missions require far-infrared array detectors with superb sensitivity, noise immunity, photometric accuracy, and electron well-depths. Current photoconductor arrays meet some of these requirements, but not all. Based on models of SMEX and SOFIA instruments designed to efficiently map interstellar magnetic fields, required detector array properties can be developed quantitatively. Future far-infrared detector arrays must meet these requirements to enable opening up the study of magnetic fields in space.

(3-02) **A Redshift Distribution of SCUBA Submm Galaxies through Keck Spectroscopy, and Modeling of the Population**

Scott Chapman, I. Smail, A. Blain, R. Ivison (CalTech)

We have obtained Keck spectroscopic identifications for a large number of sub-mm luminous galaxies, selected from SCUBA surveys on the JCMT. Comparison of the sample with Monte Carlo simulations of the total population reveals the nature of the overall population and the biases inherent in radio selection of sub-mm sources. We highlight the importance of wide bandwidth heterodyne instruments to fill in the redshifts for the submm sources missing from our surveys.

(3-03) **Optically Faint Counterparts to the ISO-FIRBACK 170Micron Population: the Discovery of Cold, Luminous Galaxies at High Redshift**

Scott Chapman, G. Helou (CalTech)

We present Keck spectroscopy and near-IR imaging observations of two 170micron sources from the ISO-FIRBACK survey which have faint counterparts in the optical, and $r-K \sim 5$. Both sources were expected to lie at $z > 1$ based on their far-infrared, submillimeter and radio fluxes, assuming a similar spectral energy distribution to the local ultra-luminous infrared galaxy (ULIRG) Arp220. However, our spectroscopy indicates that the redshifts of these galaxies are $z < 1$. While the bolometric luminosities of both galaxies are similar to Arp220, it appears that the dust emission in these systems has a characteristic temperature of $\sim 30K$, much cooler than the $50K$ seen in Arp220. If these galaxies are characteristic of the optically faint FIRBACK population, then evolutionary models of the far-infrared background must include a substantial population of cold, luminous galaxies.

(3-04) **THUMPER - A 200-Micron Camera for the JCMT**

Rhodri Evans, Derek Ward-Thompson, Peter Ade, Walter Gear, Matt Griffin, Sarah Leeks, Richard Walker (Cardiff University)

We are building a Two HUNDred Micron PhotometER (THUMPER) for the 15-m James Clerk Maxwell Telescope in Hawaii. Taking advantage of a narrow atmospheric window that opens up at this wavelength on high, dry sites, THUMPER will make continuum observations at 200-microns from the ground with unprecedented 7-arcsecond angular resolution. The focal plane comprises a hexagonal close-packed array of seven stressed Ge:Ga photoconductors fed by individual Winston cones and operating at $3.7K$. The detectors are read out by TIA amplifiers using cold JFET pairs. THUMPER is being designed to work in parallel with SCUBA using a dichroic beam-splitter. The data will be handled by the SCUBA data acquisition system, enabling all SCUBA users to see the THUMPER instrument as an additional short-wavelength sub-mm array. The instrument is planned to be in operation by early 2003. The predicted NEFD under good conditions ($0.5mm$ of pwv) is around $20 \text{ Jy/Hz}^{1/2}$.

(3-05) **Initial Test Results of SBRC-190, a Multi-Gain, Cryogenic Readout Multiplexer for IR Detector Arrays**

Jam Farhoomand, David Sisson, Lunming Yuen, Dzung Hoang (TechnoScience Corp./NASA-Ames)

SBRC-190 readout multiplexer - manufactured by Raytheon Infrared Operation - is a 1x32, multi-gain, capacitive transimpedance amplifier (CTIA) especially suitable for use with infrared detector arrays requiring low-bias levels – such as Ge:Ga far infrared detector arrays. The unit-cell design is based on the CRC-696 multiplexer which has been incorporated in SIRTf's MIPS instrument. In this presentation we will report on the results of the first set of tests conducted on several of these devices. We will discuss gain, uniformity, and read noise of the bare mux under correlated-double sampling at 4.2K.

(3-06) **The Development of a 30-125 Micron Array for Airborne Astronomy**

Christopher Mason (SETI Institute), Jessie L. Dotson (NASA-Ames), Christopher T. Koerber (TechnoScience/NASA-Ames), Edwin F. Erickson, Michael R. Haas (NASA-Ames), Anita Prasad (TechnoScience Corp., currently at Intrinsix Technologies), Fred C. Witteborn (Orbital Sciences Corp.), Jam Farhoomand, David Sisson (TechnoScience/NASA-Ames)

The development of a 30-125 micron Ge:Sb photoconductor array for AIREs (Airborne Infra-Red Echelle Spectrometer) is described. The prototype array is a 2x24 module which can be close-stacked to provide larger two-dimensional formats. Light is focused onto each detector using a collecting cone with a 2-mm pitch. The array is read out by two Raytheon SBRC-190 cryogenic multiplexers that also provide a CTIA (capacitive transimpedance amplifier) unit cell for each detector. We are conducting a series of tests to measure the array performance and to evaluate its suitability for airborne astronomy and will report our preliminary results.

(3-07) **Evaluation of Cryogenic Readout Electronics for ASTRO-F**

Toyoki Watabe, Takanori Hirao, Hiroshi Shibai, Mitsunobu Kawada, Hiroshi Nagata, Yasunori Hibi, Manabu Noda (Nagoya University)

Cryogenic readout electronics have been developed for the far-infrared detectors onboard ASTRO-F, the first Japanese infrared astronomical satellite. This cryogenic readout circuit should be mounted near the detector array at the liquid helium temperature in order to achieve high sensitivity. We succeeded in developing the cryogenic p-MOS transistor by a standard Bi-CMOS process with a slight modification. By using the new p-MOS transistor, we have made several types of cryogenic electronics, (OP-AMP and CTIA), and evaluated their performances in the liquid helium temperature. The results are:

1. Open loop gain of OP-AMP ~300
2. Input equivalence noise ~3 μ V/Hz^{1/2}
3. Power consumption ~10 μ W/ch

More details will be shown on the poster.

(3-08) **Transient Modeling and Measurements for Ge:Ga Photoconductors**

William Schwartz, Matthew Smylie, Nancy M. Haegel (Fairfield University)

Numerical modeling of the transient response of Ge:Ga photoconductors has provided insight into the cause of the hook behavior and the importance of the time scale of modulation in determining detector current output. In this poster, we will present comparisons of theoretical predictions with experimental transient behavior. Specific examples will include: 1) the effect of signal size on the extent and time constant for the hook effect, 2) the direct determination of gain values based on the transient response and 3) direct comparisons of experimental and simulated transient response.

(3-09) **Far Infrared Photovoltage Effect in a Blocked Impurity Band Photodetector**

Jean Leotin (Université Paul Sabatier, France), V.V. Rylkov, D.YU. Kovalev, B.A. Aronzon (Russian Research Center, Kurchatov Institute, Russia)

A photovoltage was found across a silicon blocked impurity band (BIB) detector when illuminated at low temperatures with photons of wavelengths up to about 30 μ m. It appears as a short circuit photocurrent changing linearly with photon flux. However, the open loop photovoltage remains constant over a wide

range of incident flux intensity. The device is a boron-doped epitaxial structure, sandwiched between degenerately doped thin semitransparent contacts, consists of a pure layer next to a photo-active layer doped in the regime where impurity banding occurs. The short-circuit photocurrent is shown to originate from a ballistic transport across the micrometer thick pure layer of holes photoexcited at the degenerately doped contact with the pure layer. Potential applications of this novel FIR photodetection mechanism will be considered.

(3-10) **4.2K Multichannel Readout Circuitry in a Standard 0.7-Micron CMOS Process for a Photoconductor Array Camera**

Ybe Creten, Patrick Merken, Jan Putzeys, Chris Van Hoof (IMEC, MCP division, Belgium)

The cryogenic design and cryogenic performance of a cold CMOS multichannel readout circuit to be used in the Photoconductor Array Camera and Spectrometer (PACS) aboard the Herschel Space Observatory is presented. The overall architecture of each of the 18 readout channels consists of a self-biasing AC-coupled capacitive feedback transimpedance amplifier, a sample-and-hold stage and a buffer. All blocks will be presented in detail. Where cryogenic (<30K) circuit design tended to be empirical and dedicated process technologies have been used, we have improved in both areas. We have used a standard CMOS foundry for better portability and scalability of our designs. In addition, we have developed robust design strategies and architectures and have successfully used a commercial simulator (SpectreS) with experimentally extracted 4K transistor model parameters. This has lead to high-gain (>2000 at 4K) and low hysteresis (below 5mV), a nonlinearity below 2% (even below 1% for the larger integration capacitors), an input noise spectral density within specifications (e.g. below 100nV/sqrtHz above 20Hz and 1uV/sqrtHz at 1Hz) and a power dissipation below 100microWatt for the entire circuit.

(3-11) **Far-IR Calibration Sources for Cryogenic Focal Planes**

Jeff Beeman (LBNL), Eugene E. Haller (UC Berkeley/LBNL)

Photoconductor and bolometer arrays used in cryogenic telescopes often suffer from response variations to a given photon flux. Thermal drifts, ionizing radiation absorption, and changes in optical components and their alignment can all effect photometric accuracy. A stable, low power, in-situ calibration lamp can help quantify and mitigate these effects without substantially diminishing cryogen (and therefore observation) lifetime. We have developed a small, lightweight IR source, based on a reverse-bolometer approach, that can achieve a greybody output (10K to 300K nominal) with a few mW input power. They have survived cryogenic shake testing, are repeatable within 0.8% over 94,000 cycles, and can be mounted directly to a cryogenic surface. Design details and performance results will be discussed.

(3-12) **High-Purity LPE GaAs for Far Infrared Blocked Impurity Band Detectors**

Ben Cardozo (UC Berkeley/LBNL), Jeff Beeman (LBNL), Eugene E. Haller (UC Berkeley/LBNL)

Blocked impurity band (BIB) devices are under development in response to the need for photoconductor detectors that operate beyond 220mm wavelength. GaAs is an ideal material for this purpose due to its 6meV donor electron binding energy. To meet the extreme purity requirements of a BIB blocking layer we have constructed a liquid phase epitaxy system dedicated to GaAs crystal growth. Epilayers are grown out of a saturated Ga/GaAs solution contained by a high purity graphite crucible. Growth is performed from 800 to 40°C with an H₂ ambient inside a quartz reactor. To ensure high purity epilayers, the crucible is periodically baked out at 1500°C in vacuum (for one to two days) to remove volatile impurities. In the near future, sapphire will be explored as an alternate material for the crucible. To date the highest purity epilayers grown have been found to be of mixed type, with an average net-doping concentration Nd-Na of $5 \times 10^{11} \text{cm}^{-3}$ through capacitance-voltage measurements.

(3-13) **Transient Effects of IR Photodetectors: the Lessons from ISO**

Alain Coulais, Alain Abergel (CNRS/IAS, France)

A large number of low background photodetectors were used on the ISO satellite, covering wavelengths from 2 to 200 microns. All these detectors were affected by transient responses after changes of incoming flux. For several detectors, it is possible to reproduce these transient responses using physical

or empirical models, with a typical accuracy of few percent. In these cases, the data can be corrected with a comparable accuracy, so that the limiting factors become the effects of High Energetic Particles and the absolute sensitivity of the instruments. We have shown that the accuracy of the modeling of the transient effects is strongly related to: (1) the design and the quality of the whole system (electronic linearity, optics, temperature control, etc.), (2) the quality of the detectors and the choice of the setups, which is to obtain reproducible transients (3) the adequacy of the tests, in order to check system misconception and also to provide accurate data for transient modeling. This experience from ISO should be useful for SIRTf and ASTRO-F.

(3-14) Design Considerations for Large Format FIR Array Detectors

Juergen Wolf (DLR - USRA/SOFIA), Alan W. Hoffman (Raytheon Infrared Operations), Jeffrey W. Beeman (LBNL), Jam Farhoomand (TechnoScience Corp./NASA-Ames)

Efficient long wavelength broadband and spectral imaging on SOFIA and in future FIR/sub-mm missions will require large two-dimensional detector arrays. While monolithic near infrared arrays of up to 2048 x 2048 pixels are available, observations at wavelengths beyond 40 microns are still limited to mosaics of 32 x 32 or less pixels. We describe how to combine state-of-the-art FIR/sub-mm photoconductor technology and the elaborate industrial production techniques of the near and mid-infrared to produce larger, more reliable and eventually easier to make long wavelength arrays. This approach includes monolithic photoconductor array configurations optimized for quantum efficiency and dark current. For electrical connection to a two-dimensional readout chip indium bump bonds similar to those in shorter wavelengths large-format arrays are used. The readout is based on the successful cryo-CMOS technology developed for SIRTf and SOFIA/AIRES. Differences in thermal contraction between detector and readout materials are addressed using techniques developed for large HgCdTe arrays. Initially, we plan on extrinsic Germanium photoconductor arrays of up to 128 x 128 pixels for wavelengths out to 130 microns. Longer wavelengths can be covered as blocked-impurity band Germanium, GaAs or other new detectors become available. Larger arrays may become feasible once the design concepts have been proven.

(3-15) The SBRC-190: A Cryogenic Multiplexer for Moderate-Background FIR Astronomy

Edwin Erickson (NASA-Ames), Erick T. Young (Steward Observatory/U of Arizona), Juergen Wolf (DLR), James F. Asbrock, Nancy Lum (Raytheon IR Operations)

The SBRC 190, a cryogenic multiplexer developed for far-infrared (FIR) photoconductor detectors operating at moderate backgrounds, is described. The circuit is based on the 32-channel CRC 696 CMOS device used on SIRTf. For applications such as encountered on SOFIA or Herschel, the new device permits higher backgrounds, a wider range of backgrounds, faster sampling, and enhanced synchronization of sampling with chopping. A relationship between sampling efficiency and noise requirements needed to achieve background-limited instrument (BLIP) performance is derived. Major design differences relative to the CRC 696 which have been incorporated in the SBRC 190 are: (a) an AC coupled, capacitive-feedback transimpedance unit cell, to minimize input offset effects, thereby enabling low detector biases, (b) selectable feedback capacitors to enable operation over a wide range of backgrounds, and (c) clamp and sample & hold output circuits to improve sampling efficiency, which is a concern at the high readout rates required. We discuss the requirements, design, fabrication issues, and expected performance.

(3-16) Germanium Blocked Impurity Band Detectors

Supriya Goyal (LBNL), Jordana Bandaru (JPL), Jeffrey W. Beeman (LBNL), Eugene E. Haller (UC Berkeley/LBNL)

Ge:Sb BIB detectors have been fabricated by growing an Sb doped IR active layer (typically 40 micrometers) on pure Ge <111> oriented substrate wafers by Liquid Phase Epitaxy (LPE) from a Pb solution, and thinning the pure wafer to a thickness of 10 micrometers. Extended long wavelength response to $\sim 50 \text{ cm}^{-1}$ which rapidly increases with bias has been observed in Ge:Sb BIB detectors with $N_d \sim 1 \times 10^{16} \text{ cm}^{-3}$. The responsivity at long wavelengths is lower than expected. This can be attributed to Sb diffusion from the IR active layer into the blocking layer during LPE growth. BIB modeling indicates

that this Sb concentration profile increases the electric field in the transition region and reduces the field in the blocking layer. A minority acceptor concentration of $\sim 2 \times 10^{12} \text{ cm}^{-3}$ was determined by Hall effect and C-V measurements on a BIB device, corresponding to an estimated depletion width ~ 1.5 micrometer.

(3-17) Evaluation of Transient Behavior of Ge:Ga detectors for ASTRO-F

Hidehiro Kaneda, Midori Akazaki, Shuji Matsuura, Takao Nakagawa, Michail Patrashin, Yousuke Isozaki, Mai Shirahata (ISAS, Japan), Mikio Fujiwara (CRL), Yoshihiko Okamura (NASDA), Mitsunobu Kawada, Hiroshi Shibai, Takanori Hirao, Toyoki Watabe (Nagoya University)

Two types of far infrared detectors, the direct hybrid Ge:Ga array and the stressed Ge:Ga array, are to be on-board the next Japanese infrared astronomical satellite ASTRO-F. As a part of pre-launch calibration of the detectors, we investigated transient properties of single-element stressed and unstressed Ge:Ga detectors. We measured the transient response under wide ranges of signal and background photon influxes. To estimate the effects of cosmic-ray hitting, we also performed gamma-ray irradiation of the detector by radioactive sources ^{60}Co and ^{137}Cs , and investigated differences in detector performance before and after the irradiation. We summarize the experimentally observed transient characteristics in our detectors at various operating conditions, including the radiation effects. At present, measurements of the transient effects in a flight model replica of the direct hybrid Ge:Ga array are underway. We also present our recent results on measurements of transient properties peculiar to the detector array.

(3-18) Advanced HEMT MMIC Circuits for Millimeter and Submillimeter-wave Power Sources

Lorene Samoska, Alejandro Peralta (JPL)

This paper focuses on InP-based, HEMT Monolithic Millimeter-wave Integrated Circuit (MMIC) power amplifiers for applications to heterodyne receivers, transmitters, and communications circuits. Recently, we have developed several HEMT MMIC circuits using HRL Laboratories' 0.1 micron InP HEMT technology with unprecedented high frequency performance and output power. Our results include an 80 GHz bandwidth power amplifier to 145 GHz, a 15-25-mW amplifier to 170 GHz and a HEMT active doubler to 300 GHz, the highest frequency HEMT doubler circuit reported to date. We will report on the design and testing of the circuits, and discuss the methods involved in measuring MMICs above 200 GHz. These circuits are particularly useful in local oscillators for heterodyne receivers at THz frequencies.

(3-19) Optoelectronic Terahertz Sources Based on Photomixers

Pin Chen, Peter H. Siegel, Herbert M. Pickett, John C. Pearson (JPL), Rolf A. Wyss (JPL, currently at Alephlightgate), Andrea Neto (JPL, currently at FEL-TNO), Arthur C. Gossard (UCSB)

Molecular line observation in the THz region using heterodyne receivers is a powerful way to investigate the chemistry and physics of the interstellar medium. However, THz heterodyne observation's potential is far from being fully realized due to source-technology limitations. The available solid-state, CW sources with enough power to serve as local oscillators (LOs) above ~ 1 THz are currently limited to $\sim 10\%$ in bandwidth and 1.6 THz in maximum frequency. Additionally, the lack of high spectral purity, frequency-agile sources hinders laboratory spectroscopy, and receiver/component characterization. We are developing traveling-wave photomixers and laser systems to overcome these impediments. Our goals include providing space-borne LO technology for (HEB) mixers to over 3 THz and portable, automated signal sources for characterization of THz receivers/components as well as laboratory spectroscopy. The state of research will be presented along with discussions of requirements for THz LOs and laboratory test sources, and the photomixer approach's unique advantages.

(3-20) Tantalum Hot-Electron Bolometers for Heterodyne Receivers

Anders Skalar, William R. McGrath, Bruce Bumble, Henry G. LeDuc (JPL)

In recent years superconducting HEB mixers have been applied to high-resolution spectroscopy at frequencies exceeding 1 THz, with instruments being built for platforms such as Herschel and SOFIA. In theory, bolometers with lower transition temperatures (T_c) than the Nb and NbN devices that are used today should yield lower mixer input noise and reduced requirements on local oscillator power. We are

therefore investigating a different material, tantalum, which can have T_c 's of about 3 K (in thin films), and can have sufficiently low film resistance (and therefore high heat conductance) that it should rival Nb with regard to intermediate frequency bandwidth. Submicron-size devices (length = 0.4 micron, width=0.2 micron) that have been fabricated for this study have resistances of 36 ohms/square, a supercurrent of up to 40 microA (at 0.4 K), and a transition temperature of 2.3 K with a narrow transition width of about 0.2 K. A He3 test receiver has been equipped to measure mixer performance both at microwave frequencies (1 to 18 GHz) and submillimeter wavelengths down to an ambient temperature of 0.4 K, and the most recent rf results of bandwidth and noise will be presented at the workshop. This work was supported by NASA.

(3-21) An Extremely Wide Bandwidth, Low Noise SIS Heterodyne Receiver Design for Millimeter and Submillimeter Observations

Matthew Sumner, Frank Rice (CalTech), Robert Hu (U of Michigan), Jonas Zmuidzinas (CalTech)

Millimeter and submillimeter heterodyne receivers using state-of-the-art superconductor-insulator-superconductor (SIS) detectors are capable of extremely large instantaneous bandwidths with noise temperatures within a few Kelvin of the quantum limit. We present the design for a broadband, sensitive, heterodyne spectrometer under development for the Caltech Submillimeter Observatory (CSO). The 180-300 GHz double-sideband design uses a single SIS device excited by a full bandwidth, fixed-tuned waveguide probe on a silicon substrate. The IF output (frequency limited by the MMIC low noise IF preamplifier) is 6-18 GHz, providing an instantaneous RF bandwidth of 24 GHz (double-sideband). The SIS mixer conversion loss should be no more than 1-2dB with mixer noise temperatures across the band within 10 Kelvin of the quantum limit. The single sideband receiver noise temperature goal is 70 Kelvin. The wide instantaneous bandwidth and low noise will result in an instrument capable of a variety of important astrophysical observations beyond the capabilities of current instruments. Lab testing of the receiver will begin this summer, and first light on the CSO should be in the spring of 2003.

(3-22) Diode-Laser Pumped Far-Infrared Local Oscillator Based on Semiconductor Quantum Wells

Cun-Zheng Ning, K. Kolokolov, J. Li, C.Z. Ning (NASA-Ames), D.C. Larrabee, J. Tang, G. Khodaparast, J. Kono (Rice University), S. Sasa, M. Inoue (Osaka Institute of Technology, Japan)

The goal of our research is to generate tunable FIR waves to be used as local oscillators or for other spectroscopic applications. Our approach is to use optically pumped intersubband transitions in semiconductor quantum wells. The innovative aspects of our approach include the use of InAs-AlGaSb quantum well structures, which allow the compact diode lasers of 1.5 microns in the wavelength to be used, due to the deep conduction band wells of such structures. This approach will eventually lead to compact FIR sources from a few THz up to 10 THz, a frequency range for which it is increasingly difficult to produce local oscillators using electronic means. To demonstrate the feasibility of our approach, we have conducted extensive theoretical investigation of THz generation using both optically pumped laser scheme and double-resonance difference-frequency generation (DFG) scheme. Initial experimental measurements have been conducted to characterize intersubband transition.

(3-23) Integrated Terahertz Heterodyne Focal Plane Array Receivers

Gopal Narayanan, Neal Erickson (U of Mass)

The first light heterodyne receivers for SOFIA, and the HIFI heterodyne receiver for Herschel, will be single-pixel receivers, reflecting the technological challenges of building array receivers at these frequencies. The principal technological barrier to space-qualifiable terahertz receivers is the problem of generating adequate local oscillator (LO) power from solid-state frequency multipliers. The first practical monolithic planar frequency multiplier circuits that can provide adequate power for supra-THz heterodyne receivers have recently been demonstrated by our group. We propose to build integrated heterodyne array receivers by using balanced mixers with direct waveguide-based LO coupling. Such an approach can significantly reduce the amount of LO power required to drive a terahertz focal plane array. A further reduction of the losses in the LO circuit can be achieved by integrating the last stages of the frequency multiplier chain in the array mixer blocks. We are beginning a program to develop novel, integrated focal plane array receivers for the 1.4 - 1.9 THz frequency band. The final two stages of frequency

multiplication will be integrated into the array mixer block, and waveguide power dividers and quadrature networks will be fabricated in-situ in the array block for LO distribution and injection. MMIC-based low-noise IF amplifiers for each pixel will also be integrated next to the mixers. Such an integrated, sensitive receiver system will be an important technology development for the future deployment of larger-format, flexible, broadband, heterodyne terahertz focal plane array receiver systems for space.

(3-24) Phonon Cooled Far-Infrared Hot Electron Bolometer Mixer

Heinz-Wilhelm Hübers, A. Semenov, H. Richter (DLR, Germany), K. Smirnov, G. Gol'tsman, B. Voronov (State Pedagogical University, Russia)

Heterodyne receivers for applications in astronomy need quantum-limited sensitivity. At frequencies above 1.4 THz superconducting hot electron bolometers (HEB) can be used to achieve this goal. We present results of the development of a quasi-optical phonon-cooled NbN HEB mixer for GREAT, the German heterodyne receiver for SOFIA. Different mixers with logarithmic spiral and double slot feed antennas have been investigated with respect to their noise temperature, conversion loss, linearity and beam pattern at several frequencies between 0.7 THz and 5.2 THz. At 2.5 THz a double sideband noise temperature of 2200 K was achieved. The conversion loss was 16 dB. The response of the mixer was linear up to 400 K load temperature. This performance was verified by measuring an emission line of methanol at 2.5 THz. The results demonstrate that the NbN HEB is very well suited as a mixer for FIR heterodyne receivers.

(3-25) Micromechanical Waveguide Mounts for Hot Electron Bolometer Terahertz Mixers

Michael Brandt, Karl Jacobs, C.E. Honingh, Jörg Stodolka (U of Cologne, Germany)

The superior beam matching of waveguide horn antennas to a telescope suggests using waveguide mounts even at THz-frequencies. In contrast to the more common quasi-optical (substrate lens) designs, the exceedingly small dimensions of the waveguide require novel micro-mechanical fabrication technologies. We will present a novel fabrication scheme for 1.9 THz waveguide mixers for SOFIA. Hot Electron Bolometer devices (HEB) are fabricated on 2 μm thick Si_3N_4 membrane strips. The strips are robust enough to be mounted on a separately fabricated Si support frame using an adapted flip-chip technology. Mounted onto the frame, the devices can be easily positioned and glued into a copper waveguide mount. Further developments regarding micro-mechanical processes to fabricate this copper waveguide mount and the receiving horn antenna will be presented, as well as the KOSMA Micro Assembly Station and its capabilities to handle mixer substrates.

(3-26) Low Noise SIS Mixer for the Frequency above 1 THz

Alexander Karpov, D. Miller, J. Zmuidzinis (CalTech), J.A. Stern, B. Bumble, H.G. LeDuc (JPL)

We developed a SIS mixer for the 1.1-1.25 THz band of the heterodyne receiver of Herschel space observatory. Our approach may be used up to 1.6 THz. The quasi-optical SIS mixer has two NbN/AlN/Nb junctions with the critical current 30-50 kA/cm² and the gap voltage of 3.4 mV. The tuning circuit integrated with SIS junction has the base electrode of Nb and a gold wire layer. This approach simplifies the SIS junction technology, compared to a design using NbTiN base electrode. The junction base electrode and the ground of the tuning micro strip circuit are formed in one step. The frequency of operation of the mixer is well above the gap frequency of Nb, and it behaves here as a normal metal. The resistivity of Nb at the critical temperature of 0.2 mOhm cm is below the resistivity of the best normal metal films. The measured receiver noise temperature is below 600 K.

(3-27) TES Detector Noise Limited Readout Using SQUID Multiplexers

J. Staguhr, D. Benford, J. Chervenak, S.H. Moseley, R. Shafer (NASA-Goddard), E. Grossman, K. Irwin, C. Reintsema (NIST)

The availability of superconducting Transition Edge Sensors (TES) with large numbers of individual detector pixels requires multiplexers for efficient readout. The usage of multiplexers limits the number of wires needed between the cryogenic electronics and the room temperature electronics and limits the number of required cryogenic amplifiers. We are using SQUID multiplexers to read out our TES arrays.

These bolometer arrays are used for submillimeter astronomical observations. We present results from test measurements with 8 channel SQUID multiplexers which show that the low noise level of these multiplexers allows accurate measurements of the TES Johnson noise, and that in operation, the SQUID noise is dominated by the detector noise. Multiplexers for large number of channels require a large bandwidth for the multiplexed readout signal. We discuss the resulting implications for the noise performance of these multiplexers which will be used for the readout of two dimensional TES arrays in next generation instruments.

(3-28) **SAMBA: Superconducting Antenna-coupled, Multi-frequency, Bolometric Array**

Alexey Goldin (JPL), James J. Bock (JPL), Cynthia Hunt (CalTech), Andrew E. Lange (CalTech), Henry LeDuc (JPL), Anastasios Vayonakis (CalTech), Jonas Zmuidzinas (CalTech)

We present a design for SAMBA – multipixel, multibandpolarization sensitive submillimeter instrument. Unlike traditional designs like SCUBA and BOLOCAM, SAMBA uses slot antenna coupled bolometers and microstrip filters. The concept allows for a much more compact, multiband imager compared to a comparable feedhorn-coupled bolometric system. Each pixel is a phased array of slot antennae with synthesized F/3.3 wide beam sensitive to wide band (up to 30% relative bandwidth) and both linear polarizations. The incoming radiation is summed by microstrip network and deposited into two (one for each polarization) resistors terminating the transmission line. The transition edge bolometers measure the millimeter-wave power. The whole focal plane is photolithographed on one wafer, simplifying assembly and allowing for simpler and lighter low

(3-29) **Absorber Coupled Transition-Edge-Sensor Bolometer Arrays for Submillimeter Imaging**

James Chervenak, Johannes Staguhn, Dominic Benford, Rick Shafer, Harvey Moseley (NASA-Goddard)

We describe the design, fabrication, and performance of transition edge sensor pixels for instruments with filled focal planes for submillimeter imaging such as SAFIRE, SPIFI, and FIBRE. We present results on the status of superconducting transition edge sensor (TES) bolometer arrays fabricated at NASA's Goddard Space Flight Center. The TES pixels consist of Mo/Au superconducting bilayers coupled to Bi absorbers on silicon nitride membranes. Recent research has focused on improving the noise performance of detector arrays, yielding appropriate bias power and dynamic range, and improving absorption efficiency as well as engineering robust structures suitable for 1000-element arrays. In the FIBRE instrument, we have demonstrated the ability of these detectors to perform with optical loading in laboratory and observatory environments.

(3-30) **SAFIRE: Far-Infrared Imaging Spectroscopy with SOFIA**

S. Harvey Moseley, Dominic Benford, Jay Chervenak (NASA-Goddard), Kent Irwin (NIST), François Pajot (IAS), Rick Shafer (NASA-Goddard), Johannes Staguhn (NASA-Goddard/SSAI), Gordon Stacey (Cornell)

The SOFIA airborne observatory will provide a high spatial resolution, low background telescope for far-infrared astrophysical investigations. Selected as a PI instrument for SOFIA, SAFIRE is an imaging Fabry-Perot spectrograph covering 145 μ m-655 μ m, with spectral resolving power of \sim 1500 (200km/s). This resolution is well matched to extragalactic emission lines and yields the greatest sensitivity for line detection. SAFIRE will make important scientific contributions to the study of the powering of ULIRGs and AGN, the role of CII cooling in extragalactic star formation, the evolution of matter in the early Universe, and the energetics of the Galactic center. SAFIRE will employ a two- dimensional pop-up bolometer array to provide background-limited imaging spectrometry. Superconducting transition edge bolometers and SQUID amplifiers have been developed for these detectors.

(3-31) **Thousand-Element Multiplexed Superconducting Bolometer Arrays**

Dominic Benford, Jay Chervenak, George Voellmer (NASA-Goddard), Johannes Staguhn (NASA-Goddard/SSAI), Rick Shafer (NASA-Goddard), Gordon Stacey (Cornell), Kent Irwin (NIST)

Large format, two-dimensional arrays of close-packed bolometers will enable submillimeter cameras and spectrometers to obtain images and spectra orders of magnitude faster than present instruments. The South Pole Imaging Fabry-Perot Interferometer (SPIFI) for the AST/RO observatory and the Submillimeter and Far-InfraRed Experiment (SAFIRE) on the SOFIA airborne observatory will employ a

large-format, two-dimensional, close-packed bolometer arrays. Both these instruments are imaging Fabry-Perot spectrometers operating at wavelengths between 100 μ m and 700 μ m. The array format is 16x32 pixels, using a 32-element multiplexer developed in part for this purpose. The low backgrounds achieved in spectroscopy require very sensitive detectors with NEPs of order 5×10^{-18} W/Hz^{1/2}. Superconducting detectors can be close-packed using the Pop-Up Detector (PUD) format, and SQUID multiplexers operating at the detector base temperature can be intimately coupled to them. We are fabricating an engineering model array with this technology which features a very compact, modular approach for large format arrays.

(3-32) Multiplexing Superconducting Bolometer Arrays

Rick Shafer (NASA-Goddard), Kent Irwin (NIST), Harvey Moseley (NASA-Goddard), Johannes Staguhn (NASA-Goddard/SSAI), Dominic Benford (NASA-Goddard), Ernie Buchanan (NASA-Goddard/SSAI), Umesh Patel (NASA-Goddard), Erich Grossman, Gene Hilton, Sae Woo Nam, Carl Reintsema (NIST), Piet de Korte (NIST/SRON), Joern Beyer (NIST/PTB Berlin)

The next generation of far-infrared and submillimeter instruments require large arrays of detectors containing thousands of elements. A multiplexed readout is necessary for practical implementation of such arrays, and can be developed using SQUIDs coupled to superconducting bolometer arrays. In this implementation, a 32x32 array of bolometers can be read out using ~100 wires rather than the >2000 needed for direct wiring. We describe the development of multiplexing as a step toward bringing about the first astronomically useful bolometer arrays of this design. We have implemented time-domain multiplexing, as this has several practical – although no theoretical – advantages over frequency-division multiplexing. New electronics and software have been developed to implement this multiplexing scheme, which has resulted in the first multiplexed detection of submillimeter light and the first multiplexed astronomical observations. We have demonstrated the ability of these! multiplexers to transduce the Johnson noise of detectors with negligible additional noise. Recent improvements in the multiplexer design have allowed us to further simplify and improve the system performance, including the development of cryogenic address selection logic.

(3-33) Mission Requirements for Ultralow-background Large-format Bolometer Arrays

Dominic Benford, Harvey Moseley, Jay Chervenak (NASA-Goddard)

In the coming decade, work will commence in earnest on large cryogenic far-infrared telescopes (e.g., SAFIR) and interferometers (SPIRIT, SPECS). These missions require large format, two-dimensional arrays of close-packed detectors capable of reaching the fundamental limits imposed by the very low photon backgrounds present in deep space. In the near term, bolometer array architectures which permit 1000 pixels – perhaps sufficient for the next generation of space-based instruments – can be arrayed efficiently. Demonstrating the necessary performance, with Noise Equivalent Powers (NEPs) of order 10^{-20} W/Hz^{1/2}, will be a hurdle in the coming years. Superconducting bolometer arrays are a promising technology for providing both the performance and the array size necessary. We discuss the requirements for future detector arrays in the far-infrared and submillimeter, describe the parameters of superconducting bolometer arrays able to meet these requirements, and detail the present and near future technology of superconducting bolometer arrays. Of particular note is the coming development of large format planar arrays with absorber-coupled and antenna-coupled bolometers.

(3-34) Single Pixel, Single Band Microstrip Antenna for Sub-Millimeter Wavelength Detection Using Transition Edge Superconducting Bolometric Receivers

Cynthia Hunt (CalTech), Jamie J. Bock, Peter K. Day, Alexey Goldin (JPL), Andrew E. Lange (CalTech), Henry G. LeDuc (JPL), Anastasios Vayonakis, Jonas Zmuidzinas (CalTech)

We are developing a single pixel antenna coupled bolometric detector as a precursor to the SAMBA (Superconducting Antenna-coupled Multi-frequency Bolometric Array) instrument. Our device consists of a dual slot microstrip antenna coupled to an Al/Ti/Au voltage-biased transition edge superconducting bolometer (TES). The coupling architecture involves propagating the signal along superconducting microstrip lines and terminating the lines at a normal metal resistor on a thermally isolated island. The device, which is inherently polarization sensitive, is optimized to for 100GHz band measurements, ideal

for future implementation as an astronomical sub-millimeter instrument. We will present recent tests of these single pixel detectors.

(3-35) **The Potential Benefits of Multimode Polarization and Frequency Selective Bolometers**

John Ruhl (UCSB/Case Western Reserve University), Stephan Meyer (U of Chicago)

We describe the benefits of using a focal plane based on multimoded polarization and frequency selective bolometers for studies of polarization in the cosmic microwave background, and discuss an approach for building such detectors.

(3-36) **Hale, a Far-Infrared Polarimeter for SOFIA**

Roger Hildebrand (U of Chicago), Jacqueline Davidson (USRA), Jessie Dotson (NASA-Ames), C. Darren Dowell (CalTech), Giles Novak (Northwestern University)

Hale is intended to be the first instrument capable of multi-wavelength polarization mapping in the far-infrared. The range of passbands, 50 to 200 microns, spans the thermal emission peaks of typical Galactic and extragalactic sources. Observations of giant molecular clouds with earlier polarimeters have shown a strong wavelength dependence of polarization in the far-infrared and beyond. The sensitivity and resolution achievable with SOFIA will make it possible to observe other types of objects such as dark clouds, infrared cirrus, and external galaxies. These sources are expected to show contrasting polarization spectra corresponding to differences in their radiation fields, thermal properties, and dust populations. Hale will require two detector arrays: one for each of two components of polarization. The arrays must operate efficiently throughout the desired range of wavelengths. The pixel size must be small enough at each passband to exploit SOFIA's superior angular resolution. To the extent possible, however, the arrays should fill SOFIA's useful focal plane with diffraction-limited and background-limited detectors.

(3-37) **Development of High and Mid Tc Transition Edge Superconducting (TES) Bolometers on 1 to 5 μm Thick Monolithic Sapphire Substrates for Space-Based Far IR Applications**

Brook Lakew (NASA-Goddard), Shahid Aslam (Raytheon Corp.), John Brasunas (NASA)

Long duration space-based observations can be done by using radiatively cooled high Tc (~ 90 K) and mid Tc (~ 39 K) TES bolometers when the use of cryogenics or high power consuming cryocoolers are not feasible. At focal plane temperatures above 77 K and at wavelengths $>30 \mu\text{m}$ high Tc bolometers perform better than photon detectors. And with the recently discovered superconductivity of MgB_2 at 39 K, even better sensitivity can be expected from TES bolometers in the Far IR. We have already developed single pixel high Tc TES bolometers with GdBCuO thin films on sapphire substrates. The measured D^* is $2 \times 10^{10} \text{ cmHz}^{1/2}/\text{W}$. We are now developing a 2-D array of 1 to 5 μm thick monolithic sapphire membranes structure for GdBCuO and MgB_2 thin films deposition. This paper will present recently achieved milestones and the status of our detector development effort.

(3-38) **Ideal Integrating Bolometer**

Alan Kogut (NASA-Goddard)

We describe a new "ideal integrator" bolometer as a prototype for a new generation of sensitive, flexible far-IR detectors suitable for use in large arrays. The combination of a non-dissipative sensor coupled with a fast heat switch provides breakthrough capabilities in both sensitivity and operation. The bolometer temperature varies linearly with the integrated infrared power incident on the detector, and may be sampled intermittently without loss of information between samples. The sample speed and consequent dynamic range depend only on the heat switch reset cycle and can be selected in software. Between samples, the device acts as an ideal integrator with noise significantly lower than resistive bolometers. Since there is no loss of information between samples, the device is well suited for large arrays.

(3-39) **Large-Format Planar Monolithic Bolometer Arrays for Far-Infrared and Submillimeter**

Minoru Freund, D. Brent Mott, James P. Laughlin, Tina C. Chen, Alexander J. Bier, Barbara A. Campano, Rainer K. Fetting (NASA-Goddard)

For future far-infrared and submillimeter astrophysics missions like SAFAIR (Single Aperture Far Infrared Observatory) and SPECS it is essential to develop technologies for large format 2D bolometer arrays of $\sim 1000 \times 1000$ pixels. Such arrays should (a) maximize the fill factor for the focal plane, and (b) allow the use of low-noise detectors that scale well to large size, such as a Transition Edge Superconductor (TES) with multiplexed SQUID readouts. We have developed such a planar technology without use of feedhorns. Our technology does not require complicated mechanical packaging. Furthermore, they are constructed using Si wafers and readily available technologies, such as deep reactive ion etching. Here, we present the design, fabrication of prototype arrays, and the mechanical characterization of these arrays.

(3-40) **Use of High Sensitivity Bolometers on Planck High Frequency Instrument**

Michel Piat (Institut d'Astrophysique Spatiale), Jean-Michel Lamarre (IAS-LERMAPlanck-HFI Consortium)

The European Space Agency Planck satellite, planned to be launched in 2007, is dedicated to survey the sky at sub-millimeter and millimeter wavelength, and especially the Cosmic Microwave Background Anisotropy (CMB). Aboard this satellite, the High Frequency Instrument (HFI) will cover the wavelength ranging from 300 μm to 3 mm by using 48 bolometers cooled to 100 mK thanks to a $^3\text{He}/^4\text{He}$ dilution cooler. This instrument is realized by a wide international collaboration, including United States and Canadian laboratories. The HFI will allow to measure CMB with an angular resolution of 5 arcmin and a sensitivity of $\Delta T/T = 2 \times 10^{-6}$, therefore about 1000 times more sensitive than COBE-DMR. The requirements and the global design of this instrument will be presented, especially on the detector chain that allows to reach the ultimate sensitivity given by the photon noise of the CMB at low frequency, and by the telescope thermal emission at high frequency.

(3-41) **GaAs LPE Growth Centrifuge - A Novel Facility to Produce High Purity GaAs Material**

Reinhard Katterloher (Max Planck, Garching), Gerd Jakob (MPE, Germany), Mitsuharu Konuma (MPI-FKF, Germany), Nancy Haegel (Fairfield University), Eugene E. Haller (UC Berkeley/LBNL)

GaAs photoconductive detectors could extend the spectral response cut-off up to 300 μm . A continuous progress in material research has led to the production of pure, lightly and heavily doped n-type GaAs layers using the liquid phase epitaxy technique (LPE). Sample detectors demonstrated the expected infrared characteristics of bulk type devices. Modeling of BIB detector types predicts an improved IR sensitivity due to the attainable higher doping of the infrared sensitive layer, but gives also an estimate of the severe material requirements for the n-type blocking layer. With a new centrifugal technique for the LPE material growth we intend to achieve this goal: Contamination from outside during the LPE growth process is reduced by a suspension of the crucible on active magnetic bearings in a completely closed environment. Technical details of this unique equipment, first results of the achieved material quality in the initial growth runs and future steps to optimize operational parameters will be reported.

(3-42) **Submillimeter Wave Superconducting Hot-Electron Direct Detectors**

Boris Karasik, Bertrand Delaet, William R. McGrath (JPL), Jian Wei, Michael E. Gershenson (Rutgers University), Andrew V. Sergeev (Wayne State University)

We are developing a new type of hot-electron direct detector (HEDD) which employs a weak electron-phonon coupling in superconducting microbridges. Such a detector with a potential NEP of $10^{-20} \text{ W/Hz}^{1/2}$ will meet the needs for future background-limited arrays on space telescopes. The HEDD is based on a 1-micron-size transition edge sensor fabricated from an ultra-thin film of a superconductor with $T_C = 0.1\text{--}0.3 \text{ K}$. The strong temperature dependence of the electron-phonon coupling in impure superconductors allows for adjustment of the electron-phonon scattering time to the desirable value of $\sim 1 \text{ ms}$. Thus, the HEDD eliminates the need in a micromachined, high-thermal-resistance suspension. The radiation frequency response of prototype antenna-coupled Nb devices has been found to be flat over the range

250-1000 GHz. Our current effort is aimed at the demonstration of a planar antenna-coupled Ti HEDD at 300-600 GHz.

(3-43) Design and Fabrication of a THz Nanoklystron

Harish Manohara, Peter H. Siegel, Colleen Marrese (JPL), Jimmy Xu, Baohe Chang (Brown University)

Recently the authors proposed a novel monolithic tube approach to THz power generation: the nanoklystron. In this presentation they report design and fabrication details of 1200 GHz nanoklystron circuits and ongoing efforts to produce low voltage cold cathodes from carbon nanotube (CNT) emitters. Both silicon-based and metal nanoklystron cavities have now been completed, and measurements on the field emission properties of several CNT cathodes have been made. In addition new techniques for growing highly ordered CNT arrays on flat evaporated surfaces have been demonstrated for the first time. The presentation will include analytic design details for the 1200 GHz nanoklystron circuit, fabrication process steps for realizing the monolithic cavity, CNT emission measurements and progress on a UHV cathode test chamber.

(3-44) Detection of Terahertz Light with Intersubband Transitions in Semiconductor Quantum Wells

Carey Cates, B. Serapiglia, Y. Dora, J. Heyman, J.B. Williams, M.S. Sherwin (Physics Dept., UC Santa Barbara), K. Campman, K.D. Maranowski, A.C. Gossard (Materials Dept., UC Santa Barbara), W.R. McGrath (JPL)

Intersubband transitions in semiconductor quantum well heterostructures are a promising approach for THz frequency detectors. Many different detection mechanisms are possible, and the high degree of control in these materials systems allows great flexibility of design. We have fabricated transistor-like devices from GaAs/AlGaAs heterostructures with intersubband transitions that are voltage-tunable in a range of frequencies between 2.5 and 3.5THz. Detection has been observed by in-plane photoconductivity due to electron heating and by gate photovoltage due to optical rectification. These devices have been designed to include diagnostic capabilities so that the electron intersubband dynamics can be studied.

(3-45) Transferred Substrate Heterojunction Bipolar Transistors for Millimeter and Submillimeter Wave Applications

Andy Fung, Lorene Samoska, Peter Siegel (JPL)

We report on our effort to develop the world's fastest transistors with the ultimate goal of utilizing them in electronic devices for advancing the present state of RF electronic systems. The approach we follow is to optimize the structure of Indium Phosphide (InP) Heterojunction Bipolar Transistors (HBTs), and to minimize device parasitics so that we may maximize the high frequency performance of the transistors. By performing a process of Transferred Substrate we are able to reduce parasitics such as the base-collector capacitance of the transistors, and also reduce parasitics related to the InP substrate. Presently we have demonstrated HBTs with f_t and f_{max} of 126 and 120 GHz, respectively in a conventional 2-micron contact lithography process without Transferred Substrate. These figures of merit are expected to improve substantially with the Transferred Substrate process that we are currently implementing. Performance enhancement of these HBTs will enable advanced high frequency amplifiers, voltage controlled oscillators, active multipliers as well as traditional high speed digital circuits.

(3-46) The Millimeter-Wave Properties of Superconducting Microstrip Lines

Anastasios Vayonakis (CalTech), C. Luo (MIT), H.G. Leduc (JPL), R. Schoelkopf (Yale University), J. Zmuidzinas (CalTech)

We have developed a novel technique for making high quality measurements of the millimeter-wave properties of superconducting thin-film microstrip transmission lines. Our experimental technique currently covers the 75-100 GHz band. The method is based on standing wave resonances in an open ended transmission line. We obtain information on the phase velocity and loss of the microstrip. Our data for Nb/SiO/Nb lines, taken at 4.2 K and 1.6 K, can be explained by a single set of physical parameters. Our

preliminary conclusion is that the loss is dominated by the SiO dielectric, with a temperature-independent loss tangent.

(3-47) WaFIRS, a Waveguide Far-IR Spectrometer for Space-Borne Astrophysics

C. Matt Bradford (CalTech), James Bock (JPL), Lieko Earle, Jason Glenn (CASA, U of Colorado), Bret Naylor (CalTech), Hien Nguyen (JPL), Jonas Zmuidzinas (CalTech)

The increasing discovery of sources which emit the bulk of their luminosity in the far-IR and submillimeter generates the need for high-sensitivity, broadband spectroscopy at these wavelengths. To overcome the size and mass limitations of far-IR and submillimeter spectrometers, we are developing WaFIRS, a novel concept for long-wavelength spectroscopy which utilizes a parallel-plate waveguide and a curved diffraction grating. WaFIRS provides the large (~60%) instantaneous bandwidth and high throughput of a conventional grating system, but offers a dramatic reduction in volume and mass because it is inherently two-dimensional and there are no extra optical elements beyond the diffraction grating itself. The spectrometer architecture is applicable for ground-based, space-based and airborne observations. To prove the concept, we are constructing Z-Spec, a 100 mK spectrometer for use with background-limited bolometers in a 1-1.6 mm, $\lambda/D \sim 350$ submillimeter galaxy redshift machine.

(3-48) Lead Telluride-Based Photodetectors - A Promising Alternative to Doped Si and Ge

Dmitriy Khokhlov, Dmitriy Dolzhenko, Ivan Ivanchik, Konstantin Kristovskiy (Moscow State University), Dan Watson, Judy Pipher (U of Rochester), Juergen Wolf (German Aerospace Center - DLR)

Doping of lead telluride and related alloys with group III impurities results in an appearance of unique physical features of the material, such as persistent photoresponse, enhanced responsive quantum efficiency (up to 100%), high energy radiation hardness and many others. We review the physical principles of operation of photodetecting devices based on group III-doped IV-VI material including the possibilities of fast quenching of the persistent photoresponse, construction of a focal-plane array, new readout technique, and others. Comparison of performance of the state of the art Ge:Ga and Si:Sb photodetectors with their lead telluride-based analogs shows that the responsivity of PbSnTe(In) photodetectors is by several orders of magnitude higher. High photoresponse is detected at a wavelength of 116 microns in PbSnTe(In), and it is possible that the photoconductivity spectrum covers all the submillimeter wavelength range.

(3-49) Background Limited Superconducting Quantum Detector for Astronomy

Alexei Semenov, Heinz-Wilhelm Hübers, Andreas Engel, Gregory N. Gol'tsman (DLR, Germany)

We present the concept of the superconducting quantum detector for astronomy. Response to a single absorbed photon appears due to successive formation of a normal spot and phase-slip-centers in a narrow strip carrying sub-critical supercurrent. The detector simultaneously has a moderate energy resolution and a variable cut-off wavelength depending on both the material used and operation conditions. We simulated performance of the background-limited direct detector having the 100-micrometer cut-off wavelength. Low dark count rate will allow to realize 10^{-21} W Hz^{-1/2} noise equivalent power at 4 K background radiation. The intrinsic recovery time of the counter is rather determined by diffusion of nonequilibrium electrons, thus, thermal fluctuations do not hamper energy resolution of the detector. Provided an appropriate readout technique, the resolution should be better than 1/20 at 50-micrometer wavelength. Planar layout and relatively simple technology favor integration of the detector into an array.

(3-50) Limits to Efficiency of Imaging Systems

S. Harvey Moseley, Edward J. Wollack, Gary F. Hinshaw (NASA-Goddard)

The application of microelectronic techniques to the production of far infrared and submillimeter detectors has resulted in the design and production of large arrays. It is of great importance to understand the optimal approach to optically coupling these detector arrays to a telescope. In this paper, we will compare the performance of an ideal position sensitive detector to the performance of an ideal matched "Airy" feedhorn. With the development of fiber optics, this comparison is relevant for optical applications as well,

because single mode fibers can be produced with spatially coherent coupling structures. Finally, we will compare two practical detectors, a Nyquist sampled array of square pixels, and a Gaussian horn with spatial sampling.

(3-51) Resonant Terahertz Photoconductance of Grating Gated Double Quantum Well Field Effect Transistors

Xomalin Peralta, S.J. Allen (iQUEST, UC Santa Barbara), M.C. Wanke, N.E. Harff, J.A. Simmons, M.P. Lilly, J.L. Reno, W.E. Baca (Sandia National Laboratories), P.J. Burke, J.P. Eisenstein (CalTech)

Coupled double quantum well field effect transistors with a grating gate exhibit photoconductive response that resonates with standing 2-D plasmons under the gate. Readily tuned resonances occur around ~600 GHz. The response is relatively broad and uninspiring at ~ 4 K but grows and sharpens dramatically ("Q" 20) as the temperature is raised to ~ 20-40 K. The detection mechanism is not clear but we have confirmed that the resonance is controlled by the standing plasmons under the grating gate and that a coupled double quantum well is required. The role of the coupled double quantum wells is underscored by a dramatic inversion and shift of the photoconductive plasma resonance by an in plane magnetic field. Current measurements can only determine that the speed exceeds 700 nsec. The prognosis for developing a fast tunable incoherent detector or heterodyne detector will be discussed.

(3-52) Modeling of Growth Parameter Effects for Far Infrared Blocked Impurity Band Detectors

S.A. Samperi, N.M. Haegel (Fairfield University), A.M. White (White Numeric Consulting, England) 3-52

Numerical modeling has been performed as a function of compensation in the absorbing layer, net doping in the blocking layer and the extent of interface doping gradient at the absorber/blocker interface. Space charge effects cause field variations in the blocking layer at the net doping levels currently obtainable in development efforts for Ge and GaAs BIBs. Increased space charge at the absorber/blocker interface creates a field gradient, leading to reduced net field in the blocker layer and an extension of the depletion region in the absorber.

(3-53) Large Bolometer Arrays for the PACS/Herschel Instrument

Patrick Agnese (CEA/LETI/DOPT/SLIR, France), Louis Rodriguez, Laurent Vigroux (CEA/DSM/DAPNIA/Service d'Astrophysique, France)

We are developing bolometer arrays based on silicon etched absorbing grids, implanted Si thermometers, and cold readout and multiplexer MOS electronics. The performances of these arrays are well suited for the high background conditions of the PACS photometer. The sizes of the arrays, 32X64 pixels and 16X32 for the 100 microns and 170 microns channels respectively provide a full sampling of the PSF. The bolometers are cooled to 300 mK by an 3He sorption cooler. Thermal decoupling from the 2 K structure is ensured by a Kevlar suspension. Two engineering models of the focal plane have already been produced. They have experienced mechanical and thermal tests, as well as functional tests for the thermometers and the cold electronics. Absolute responsivity calibration is pending an upgrade of our test dewar. Possible evolution of this technology and constraints imposed on its utilization will be addressed.

(3-54) Cryocoolers for Space

Kittel Peter, Pat Roach, Jeff Feller (NASA-Ames), Ali Kashani, Ben Helvensteijn (Atlas Scientific)

Many of the detectors for space telescopes require cooling to increase sensitivity and reduce thermal noise. For space applications, such cooling requires reliable, long-life coolers that are relatively compact and light weight and have low vibration. We have developed or are developing coolers that meet these requirements over a wide range of temperatures. These include pulse tube coolers cooling from 300 K to below 10 K, a magnetic cooler cooling from 10 K to 2 K, a ³He sorption cooler cooling from 2 K to 0.3 K and a helium dilution cooler cooling from 0.3 K to 0.05 K. Details of these coolers and their advantages are presented.

Session 4: Coherent Detection

(4-01) **Coherent Detection and SIS Mixers**, (invited)

Jonas Zmuidzinas, Alexandre Karpov, David Miller, F. Rice (CalTech), Henry G. LeDuc, John Pearson, Jeffrey A. Stern (JPL)

The first part of this presentation will review coherent detection techniques, which are used in astrophysics primarily at long wavelengths, from the radio into the far-infrared. As compared to direct detection, coherent detection has several significant advantages, including the ability to obtain very high spectral resolution. However, these advantages must be weighed against the principal disadvantage, which is a fundamental limit to sensitivity that is imposed by quantum mechanics. The second part of the presentation will focus more closely on the status of superconducting tunnel junction (SIS) mixers, describing recent developments and exploring future directions.

(4-02) **Superconductive Hot Electron Bolometer Mixers**, (invited)

William R. McGrath, Boris Karasik, Anders Sklare (JPL), Irfan Siddiqi, Daniel Prober (Yale)

Hot electron bolometer (HEB) mixers have made exceptional progress in recent years. These superconductive devices can operate well above the energy gap where current state-of-the-art SIS mixers begin to fail. Mixing results have been reported throughout the submillimeter range, up to several THz. The bolometer consists of a simple microbridge that is biased near the center of the superconductive transition. Only about 0.1 μ W of LO power is needed to drive the mixer. HEB mixers are expected to play a central role in astrophysical observations at THz frequencies and are currently under development for the HIFI instrument on the Herschel Space Observatory, the SOFIA airborne observatory, and mountain-top observatories. This talk will provide an introduction to these unique sensors, a brief survey of the current status of the field, and some discussion of important topics related to future development.

(4-03) **THz Local Oscillator Sources**, (invited)

Imran Mehdi, Erich Schlecht, Goutam Chattopadhyay, Peter H. Siegel (JPL)

Most operational Submillimeter-wave radio telescopes, both space borne and ground based, employ local oscillator sources based on Gunn diodes followed by whisker contacted Schottky multipliers. Enough progress, however, has been made on a number of fronts to conclude that next generation of radio telescopes that become operational in the new Millennium will have a different local oscillator (LO) generation architecture. MMIC power amplifiers with impressive gain in the Ka- to-W band have enabled the use of microwave synthesizers which can then be actively multiplied to provide a frequency agile power source beyond 100 GHz. This medium power millimeter source can then be amplified to enable efficient pumping of follow-on balanced multiplier stages. Input power to the multipliers can be further enhanced by power combining to achieve close to half a Watt at W-band. An 800 GHz three-stage multiplier chain, implemented this way has demonstrated a peak output power of 1 mW. A second advance in LO generation lies in the Schottky diode varactor technology. Planar Schottky diode multipliers have now been demonstrated up to 1500 GHz and it can be assumed that most of the future multiplier chains will be based on these robust devices rather than the whisker contacted diode of the past. The ability to produce planar GaAs diode chips deep into the THz range, with submicron dimensions, has opened up a wide range of circuit design space which can be taken advantage of to improve efficiency, bandwidth, and power handling capability of the multipliers. A third breakthrough has been the demonstration of photonic based LO sources utilizing GaAs photomixers. These sources, though not yet implemented in robust space borne missions, offer a number of advantages over their electronic counterparts, including extremely broad tuning, fiber coupled components, and solid-state implementation. Another development, which holds some promise, is the use of micro-machining technology to implement fundamental THz oscillators based on vacuum tube principles, such as the nanoklystrons. This talk will present an overview of the current technologies that are available for implementing local oscillator sources for heterodyne receivers. Progress to date on specific components

will be discussed in some detail. Outstanding issues and concerns regarding practical implementation of these new technologies will also be discussed.

(4-04) **Spectrometers for Heterodyne Detection**, (invited)

Andrew Harris (U of Maryland)

As a broad characterization at submillimeter and longer wavelengths, heterodyne spectroscopy is appropriate whenever line-resolved information is important. Spectrometers with very broad bandwidths and modest to high spectral resolution are important complements to the latest generations of high-sensitivity broadband receivers. The near-term future adds applications including wideband searches for distant objects with poorly known redshifts, submillimeter and far-infrared observations of Doppler-broadened spectral lines from galaxies, hyperspectral line surveys to find chemical conditions in molecular clouds, and observations of pressure-broadened atmospheric lines. Spectrometers suitable for submillimeter and far-infrared interferometry will also become important in the future. Current spectrometer technologies include filter banks, acousto-optical spectrometers, surface wave spectrometers, digital lag correlators, and very wideband analog lag correlators. We will review these technologies and recent developments, then explore the ranges of parameter space where each is most appropriate to find the areas where the technologies are mature and where science goals will drive development.

(4-05) **Amplifier Technology for Astrophysics**, (invited)

Todd Gaier, Sander Weinreb, Mary Wells, Charles Lawrence, Douglas Dawson (JPL), Richard Lai, Ronald Grundbacher, Roger Tsai, Augusto Gutierrez, Barry Allen (TRW)

High Electron Mobility Transistor (HEMT) amplifiers have found their way into millimeter-wave receivers as ultra-low-noise front ends, low noise intermediate frequency (IF) amplifiers and coherent power generation devices for local oscillators. Our InP HEMTs have demonstrated record noise performance at 8 GHz with three times quantum-limited noise, 30 GHz with 7.5 K noise and 100 GHz with 28 K noise. MMIC application of this technology is enabling highly integrated receiver functionality in a compact package, demonstrated in the prototype development of the 100 GHz Planck-LFI receivers. The next generation CMB polarization missions will require one to two orders of magnitude sensitivity improvement over Planck. A combination of device improvements, and dense array technology will be required in order to achieve this sensitivity. The prospects for further development HEMTs was greatly improved this year with the initiation of the DARPA Antimonide Based Compound Semiconductor program which may yield devices with a factor of 2-3 improvement in noise at 100 GHz, thus approaching the quantum limit. Dense multi-function packaging techniques must also be employed in order to populate arrays with 1000 or more elements required to reach sub microKelvin sensitivities needed to detect B-mode polarization.

(4-06) **Techniques for Heterodyne Array Receivers**

David Rabanus, Urs U. Graf, Stefan Heyminck, Carl Jacobs, Rudolf Schieder, Stephan Stanko, Juergen Stutzki (U of Cologne, Germany)

We present current and possible future techniques for spatially multiplexed heterodyne receivers. The presentation comprises various ways of multiplexing LO power, dense arrangement of mixer elements in a cryogenic focal plane, manufacturing techniques of integrated optics units for reduction of optical adjustment effort, and describes an automated procedure for tuning a large number of mixer elements in short time.

Session 5: Bolometer Systems

(5-01) **Bolometric Detectors for Space Astrophysics**, (invited)

Paul Richards (UC Berkeley)

An overview will be given of the status of arrays of bolometric detectors for space astrophysics experiments from 100 to 3000 microns. First, the existing technologies based on semiconductor thermistors that are now being prepared for current space missions will be described. Second, the new opportunities provided by superconducting TES technology for large format arrays with multiplexed readouts will be described. The intention will be to help the general audience to appreciate the more specialized talks on these subjects later in the session.

(5-02) **Antenna-Coupled Bolometer Arrays for Astrophysics**, (invited)

James Bock (JPL)

Bolometers offer the best sensitivity in the far-infrared to millimeter-wave region of the electromagnetic spectrum. We are developing arrays of feedhorn-coupled bolometers for the ESA/NASA Planck Surveyor and Herschel Space Observatory. Advances in the format and sensitivity of bolometric focal plane array enables future astrophysics mission opportunities, such as CMB polarimetry and far-infrared/sub-millimeter spectral line surveys. Compared to bolometers with extended area radiation absorbers, antenna-coupled bolometers offer active volumes that are orders of magnitude smaller. Coupled to lithographed micro-strip filters and antennas, antenna-coupled bolometer arrays allow flexible focal plane architectures specialized for imaging, polarimetry, and spectroscopy. These architectures greatly reduce the mass of sub-Kelvin bolometer focal planes that drive the design of bolometric instrumentation.

(5-03) **Large Format Bolometer Arrays for Far Infrared, Submillimeter, and Millimeter Wavelength Astronomy**, (invited)

Harvey Moseley (NASA-Goddard)

Imaging, spectroscopy, and polarimetry at far infrared, submillimeter, and millimeter wavelengths promise to provide a unique new vision of the early universe and of the evolutionary processes which have produced our world. SIRTf, SOFIA, and Herschel, which are under development, will provide the means to address many questions of galaxy evolution and star formation. These missions will provide the scientific and technical base for the next generation of missions. The decadal survey has recommended the SAFIR mission to provide a high performance far infrared observatory to probe early galaxy evolution and star formation. CMBPOL was recommended to enable a search for the effects of gravitational waves in the early universe on the CMB. Both of these missions require large arrays of sensitive far infrared/mm detectors in order to meet their scientific objectives. I will describe the present state of far infrared bolometer arrays, which are the current detectors of choice beyond 200 μm , and the path towards the large format sensitive arrays required by these future missions. TES bolometers with multiplexed SQUID readouts are the strongest candidates today; they can meet sensitivity requirements, and the superconducting readout provides for easy interfaces, and low power dissipation. The production of large, high performance arrays is essential for SAFIR and CMBPOL, and is a sufficiently difficult task that it will require a coordinated effort among the entire development community to assure timely success.

(5-04) **Voltage-Biased Superconducting TES Bolometers for the Far-Infrared to Millimeter Wavelength Range**, (invited)

Adrian Lee, Sherry Cho, Jan M. Gildemeister, Nils Halverson, William Holzapfel, Jared Mehl, Mike Myers, Trevor Lanting, Paul L. Richards, Eva Rittweger, Dan Schwan, Jesse Skidmore, Jongsoo Yoon (UC Berkeley)

We are developing focal-plane arrays of superconducting bolometers with up to 1,000 elements. The sensors are voltage-biased Transition-Edge Sensors, and they are read out with SQUID amplifiers. We are developing several pixel architectures, each of which has advantages depending on the type of observation. We are developing a planar-antenna coupled bolometer, which is suitable for polarization

measurements of the CMB. Multichroic pixels are achieved by using RF-frequency multiplexers between the antenna and bolometer. These frequency multiplexers are built from superconducting microstrip transmission lines and therefore will have low loss. A wide range of bandwidths is possible with this technology with resolving powers of several to 100 or more. We are also developing horn-coupled spider-web absorber bolometers and bare filled absorber-coupled arrays. We have developed fabrication methods for building large arrays of absorber-coupled bolometers with high yield. The bolometers use silicon-nitride suspensions and micromesh absorbers. Arrays of 1,000 or more bolometers will be practical using these new methods. We will present results from prototype bolometers built with this fabrication process.

(5-05) **SQUID-Based Multiplexers for Transition Edge Sensor Readout**, (invited)

Mikko Kiviranta, Heikki Seppä (VTT Microsensing, Finland), Jan van der Kuur, Piet de Korte (SRON, Netherlands)

Theoretical background behind frequency- and time- domain multiplexing is given in the context of cryogenic readout of TES arrays. Some questions related to practical MUX implementation are covered, in particular the noise folding and dynamic range of the SQUID amplifier. Emphasis is on frequency domain multiplexing for X-ray sensors.

(5-06) **Frequency-Domain Multiplexing for Large-Scale Bolometer Arrays**, (invited)

Helmuth Spieler (LBNL)

The development of planar fabrication techniques for superconducting transition-edge sensors has brought large-scale arrays of 1000 pixels or more to the realm of practicality. This raises the problem of reading out a large number of sensors with a tractable number of connections. A possible solution is frequency-domain multiplexing. I summarize basic principles, present various circuit topologies, and discuss design trade-offs, noise performance, cross-talk and dynamic range. The design of a practical device and its readout system is described with a discussion of fabrication issues, practical limits and future prospects.

(5-07) **Fundamental Performance Limits of Time Division SQUID Multiplexers**, (invited)

Kent Irwin (NIST), Damian Audley (UK ATC), James Beall (NIST), Dominic Benford (NASA-Goddard), Joern Beyer (PTB, Berlin), Steve Deiker (NIST), Piet DeKorte (SRON, Netherlands), William Duncan (UK ATC), Gene Hilton (NIST), Wayne Holland (UK ATC), Michael MacIntosh (UK ATC), S. Harvey Moseley (NASA-Goddard), Sae Woo Nam (NIST), Carl Reintsema (NIST), Rick Shafer (NASA-Goddard), Johannes Staguhn (NASA-Goddard), Leila Vale (NIST)

SQUID multiplexers make it possible to build arrays of thousands of low-temperature bolometers based on superconducting transition-edge sensors (TES) with a manageable number of readout channels. We are developing time-division SQUID multiplexers. Our first-generation, 8-channel SQUID multiplexer has been used in FIBRE, a one-dimensional TES array for submillimeter astronomy. Our second-generation 32-pixel multiplexer, based on an improved architecture, is now being developed for submillimeter instruments including SAFIRE, which will fly on SOFIA, and SCUBA-2, a submillimeter camera with more than 12,800 pixel to be deployed on the JCMT. In spite of the scale of these instruments, we are still far from the fundamental performance limits of time-division SQUID multiplexers. We discuss the fundamental performance limits of time-division SQUID multiplexers, describe the limitations of current implementations, and discuss the development necessary to approach the fundamental limits.

(5-08) **The SHARC II 350-Micron Bolometer Array: 384 Pixels Read in "Total Power" Mode**

Charles Dowell (CalTech), Christine A. Allen, S. Harvey Moseley (NASA-Goddard), Thomas G. Phillips (CalTech), George Voellmer (NASA-Goddard)

SHARC II is a facility 350 micron camera for the Caltech Submillimeter Observatory expected to come on-line in 2002. The key component of SHARC II is a 12x32 array of doped silicon "pop-up" bolometers developed at NASA/Goddard and to be completed by March 2002. Each pixel is 1 mm X 1 mm, coated with a 400 ohms/square bismuth film, and located $\lambda/4$ above a reflective backshort to maximize radiation absorption. The pixels cover the focal plane with >95% filling factor. Each doped thermistor

occupies nearly the full area of the pixel, which results in a $1/f$ knee of the detector noise at 0.01 Hz under load at the bath temperature of 0.32K. To take advantage of the low $1/f$ noise, the bolometers are AC-biased and read in "total power" mode (B. Crill et. al., in preparation, 2002). The readout allows slow modulation of astrophysical signals (nodding or scanning), in principle without the need for fast modulation (chopping). The total power capability makes possible continuous correction for atmospheric transmission. In the best 25% of winter nights on Mauna Kea, SHARC II is expected to have an NEFD at 350 microns of $1 \text{ Jy s}^{1/2}$ or better. The new camera should be 4 times faster at detecting known point sources and 30 times faster at mapping large areas compared to its predecessor.

Session 6: Promising Future Detector Technology

(6-01) **Integrated, Heterodyne Array Receivers for FIR Spectroscopy**

Christopher Walker (U of Arizona), Daniel Prober (Yale), Jacob Kooi (CalTech), Arthur Lichtenberger (U of Virginia), Gordon Chin (NASA-Goddard), Christian Drouet d'Aubigny, Christopher Groppi, Craig Kulesa, Abigail Hedden, Dathon Golish (U of Arizona)

While the possibility of large format (~100 pixel) spectroscopic imaging cameras at submillimeter wavelengths has been discussed for more than two decades, only recently have advances in mixer technology, device fabrication, micromachining, LO sources, and digital signal processing made the construction of such an instrument possible both technically and fiscally. Here we present a design concept for a compact, heterodyne camera for SOFIA capable of providing low-noise, high spectral resolution operation up to ~10 THz (30 microns). The focal plane array utilizes micromachined, waveguide mixers with membrane-mounted HEBs. Due to the resistive nature of HEBs and the use of a wideband, waveguide mount, the bandwidth of the array mixers should be >30%. Recent advances in HEB performance using new materials suggest that significantly lower noise operation than presently obtained is possible. The array backend spectrometer could utilize array AOSs or new generation correlator technology.

(6-02) **Multiplexable Kinetic Inductance Detectors**

Jonas Zmuidzinas (CalTech), P. Day, H.G. LeDuc (JPL), B. Mazin, A. Vayonakis (CalTech)

We are developing a new type of superconducting direct detector based on the kinetic inductance effect. The novel features of our approach include operation at temperatures far below T_c and the use of microwave frequencies for the readout. The essential component is a planar thin-film resonator structure, which is easily fabricated on a dielectric substrate using lithography. The resonators have a very high Q , and consequently a large number of detectors (10^3 or more) may be frequency multiplexed using a single cryogenic amplifier. The basic concept is applicable over a very large wavelength range, and we have very recently demonstrated energy-resolved single photon X-ray detection. The presentation will focus on the physics of the detectors and their potential for realizing large format mm/submm arrays.

(6-03) **Intersubband Terahertz Detectors**

Mark Sherwin, C. Cates, G. B. Serapiglia, Y. Dora, M. Hanson, A.C. Gossard (UCSB), W. R. McGrath (JPL)

Intersubband dynamics of electrons and wide semiconductor quantum wells offer opportunities to fabricate Terahertz detectors with extremely high performance, new functionalities, and moderate cryogenic requirements. I will begin with a review of intersubband transitions in quantum wells and detectors based thereon. I will then discuss the theory and development of "Tunable antenna coupled intersubband THz" (TACIT) detectors. These are four-terminal phototransistors. Terahertz radiation absorbed via an intersubband transition changes the in-plane resistance between a source and drain. Our current research program aims to demonstrate a TACIT heterodyne receiver for 1.6 THz suitable for space-based THz astrophysics missions and operating at lattice temperatures > 20 K while requiring local oscillator power < 1 μ W. Such a device would eliminate the need to fly either liquid helium, required to cool state of the art superconducting mixers, or few-mW Terahertz sources, required to pump Schottky diode receivers.

(6-04) **Antenna-Coupled Superconducting Tunnel Junctions with Single-Electron Transistor Readout for Detection of Sub-Mm Radiation**

Thomas Stevenson, W.T. Hsieh, M.J. Li, C.M. Stahle, E.J. Wollack (NASA-Goddard), R.J. Schoelkopf, J. Tüefel (Yale University)

Antenna-coupled superconducting tunnel junction detectors have the potential for photon-counting sensitivity at sub-mm wavelengths. The device consists of an antenna structure to couple radiation into a small superconducting volume and cause quasiparticle excitations, and a single-electron transistor to measure currents through tunnel junction contacts to the absorber volume. We will describe optimization

of device parameters, and recent results on fabrication techniques for producing devices with high yield for detector arrays. We will also present modeling of expected saturation power levels, antenna coupling, and RF multiplexing schemes.

(6-05) Development of Microshutter Arrays for the Near Infrared Spectrometer on NGST

Robert Silverberg (LASP/NASA-Goddard), S. Aslam, K.A. Blumenstock (NASA-Goddard), R.K. Fetting, D.E. Franz (RITSS/NASA-Goddard), M. Harvey (NASA-Goddard), A.S. Kutyrev (SSAI/NASA-Goddard), J. Laughlin, M.J. Li, S.H. Moseley, D.B. Mott (NASA-Goddard), D.A. Rapchun (GST/NASA-Goddard), D.S. Schwinger, S. Manthripragada, R.P. Wesenberg, Y. Zheng (NASA-Goddard)

Field selectors greatly improve the overall performance of multi-object spectrometers because they make efficient use of the available infrared detector arrays and data handling capabilities. Here we describe a programmable multi-object field selector currently under development for use in the NGST NIRSpc. This device is a large microshutter array of 100 micron x 100 micron shutters fabricated using Micro-Electro-Mechanical Systems (MEMS) techniques. The shutters are magnetically actuated and electrostatically latched in their programmed positions. In this paper, we will discuss the design, development, performance, operation, as well as the integration and testing of these microshutter arrays.

(6-06) GaAs/AlGaAs Multi-Quantum-Well Based Far Infrared (> 30 Microns) Detectors for Astronomy Application

Sumith Bandara, S.D. Gunapala, D.Z. Ting, S.B. Rafol, J.K. Liu (JPL)

We are developing a novel broadband GaAs/AlGaAs multi-quantum-well (MQW) based far infrared detector based on intersubband absorption in shallow quantum wells. This type of MQW detectors and large format focal plane arrays (FPAs) have been successfully demonstrated in the mid- and long-wavelength infrared (LWIR) region up to 27 microns. The carrier relaxation process of these far infrared detectors are limited by the longer life-time associated with longitudinal-acoustic phonon emission process compared to the faster relaxation process in mid- and LWIR MQW detectors. As a result, the far infrared detectors based on this technology should perform better than mid- and LWIR MQW detectors. Preliminary theoretical estimates show that these MQW based far infrared detectors with 70 microns cutoff wavelength can operate at 7.2K with detectivity (D^*) exceeding 1×10^{11} Jones. As a result of mature GaAs growth and processing technology, mid- and LWIR detectors based on this technology has already demonstrated very high uniformity (< 0.02%), high operability (> 99.99%), and very low 1/f noise knee (< 10 mHz) large format (1024x1024) focal planes at lower cost. Thus, we strongly believe large format FPAs of these far infrared detectors can be achievable in near future.

(6-07) Far-Infrared Focal Plane Arrays

A.L. Betz, R.T. Boreiko (U of Colorado), S. Sivananthan, Y.D. Zhou (U of Illinois-Chicago)

The development of focal plane arrays has dramatically increased the sensitivity and efficiency of optical and infrared telescopes. The versatility of HgCdTe alloy technology has been demonstrated by detector arrays with cutoff wavelengths tailored between $\lambda_c = 1\text{-}10 \mu\text{m}$. Although the cutoff wavelength can theoretically be extended to infinity (zero gap) by increasing the HgTe mole fraction, the required accuracy of the alloy composition is difficult to achieve with conventional liquid-phase-epitaxy (LPE). The more recent technique of molecular-beam-epitaxy (MBE), on the other hand, provides the necessary precision, and detector arrays appear feasible out to $\lambda_c = 100 \mu\text{m}$. Although the alloy approach should work, an alternate device structure may prove superior. Rather than alloying HgTe and CdTe, one can deposit alternating layers of the two materials in a composite structure called a superlattice (SL). Because layer thickness (rather than alloy composition) determines the cutoff wavelength in a SL, this approach should prove easier for fabricating an $E_g = 0.01 \text{ eV}$ semiconductor. Photodiodes made from SL material should also have lower tunneling currents, which are the dominant source of noise in low gap devices. This talk will describe a NASA-funded project to develop HgCdTe detectors for FIR wavelengths. Work is now in progress on the fabrication of discrete detectors, with emphasis on the superlattice approach. Within 3 years we hope to have a 32×32 element array for $\lambda = 50\text{-}60 \mu\text{m}$. The ultimate goal is a 128×128 element array for $\lambda = 50\text{-}100 \mu\text{m}$ that could be used on a SOFIA instrument.

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PRINCIPAL AUTHORS

Name	E-mail Address	Affiliation
Agnese, Patrick	AGNESE@chartreuse.cea.fr	CEA/LETI/DOPT/SLIR, France
Bandara, Sumith	sumith.v.bandara@jpl.nasa.gov	JPL
Beeman, Jeff	jwbeeman@lbl.gov	LBNL
Benford, Dominic	Dominic.Benford@gsfc.nasa.gov	NASA-Goddard
Betz, Albert	betz@casa.colorado.edu	U of Colorado
Bock, James	James.Bock@jpl.nasa.gov	JPL
Bradford, C. Matt	bradford@caltech.edu	Caltech
Brandt, Michael	brandt@ph1.uni-koeln.de	Univ. of cologne
Cardozo, Ben	bcardozo@lbl.gov	UC Berkeley/LBNL
Cates, Carey	isabel@physics.ucsb.edu	UC Santa Barbara
Chapman, Scott	schapman@irastro.caltech.edu	Caltech
Chen, Pin	pin.chen@jpl.nasa.gov	JPL
Chervenak, James	jcherven@pop500.gsfc.nasa.gov	NASA-Goddard
Clemens, Dan	clemens@protostar.bu.edu	Boston University
Coulais, Alain	alain.coulais@ias.fr	CNRS (IAS and Observatoire)
Creten, Ybe	ybe.creten@imec.be	IMEC, MCP division, Belgium
Dowell, Charles	cdd@submm.caltech.edu	Caltech
Erickson, Edwin	erickson@cygnus.arc.nasa.gov	NASA-Ames
Evans, Rhodri	rhe@astro.cf.ac.uk	Cardiff University
Farhoomand, Jam	jfarhoomand@mail.arc.nasa.gov	TechnoScience Corp/NASA-Ames
Freund, Minoru	mino@stars.gsfc.nasa.gov	NASA-Goddard
Fung, Andy	andy.k.fung@jpl.nasa.gov	JPL
Gaier, Todd	todd.gaier@jpl.nasa.gov	JPL
Genzel, Reinhard	genzel@mpe.mpg.de	Max-Planck/UC Berkeley
Goldin, Alexey	Alexey.Goldin@jpl.nasa.gov	JPL
Goyal, Supriya	SGoyal@lbl.gov	LBNL
Haegel, Nancy	nhhaegel@fair1.fairfield.edu	Fairfield University
Haller, Eugene	eehaller@lbl.gov	UC Berkeley/LBNL
Harris, Andrew	harris@astro.umd.edu	University of Maryland
Hartmann, Gernot	gernot.hartmann@dlr.de	DLR, Germany
Hildebrand, Roger	roger@oddjob.uchicago.edu	University of Chicago
Hübers, Heinz-Wilhelm	heinz-wilhelm.huebers@dlr.de	DLR
Hunt, Cynthia	cynthiah@its.caltech.edu	Caltech
Irwin, Kent	irwin@boulder.nist.gov	NIST
Kaneda, Hidehiro	kaneda@ir.isas.ac.jp	ISAS, Japan
Karasik, Boris	boris.s.karasik@jpl.nasa.gov	JPL
Karpov, Alexander	karpov@submm.caltech.edu	Caltech
Katterloher, Reinhard	rok@mpe.mpg.de	Max-Planck, Garching
Khokhlov, Dmitriy	khokhlov@mig.phys.msu.su	Phys Dept, Moscow State University
Kittel, Peter	pkittel@mail.arc.nasa.gov	NASA-Ames
Kiviranta, Mikko	Mikko.Kiviranta@vtt.fi	VTT Microsensing
Kogut, Alan	alan.kogut@gsfc.nasa.gov	NASA-Goddard
Lakew, Brook	brook.lakew@gsfc.nasa.gov	NASA-Goddard
Lange, Andrew	ael@astro.caltech.edu	Caltech
Lee, Adrian	atl@physics.berkeley.edu	UC Berkeley
Leotin, Jean	leotin@cict.fr	Université Paul Sabatier
Manohara, Harish	harish@merlin.jpl.nasa.gov	JPL
Mason, Chris	cmasonmn@yahoo.com	SETI/NASA-Ames
Matsuura, Shuji	matsuura@ir.isas.ac.jp	ISAS, Japan
McGrath, Rob	william.r.mcgrath@jpl.nasa.gov	JPL
Mehdi, Imran	imran@merlin.jpl.nasa.gov	JPL
Moseley, Harvey	moseley@stars.gsfc.nasa.gov	NASA-Goddard
Narayanan, Gopal	gopal@astro.umass.edu	U of Mass
Ning, Cun-Zheng	cning@mail.arc.nasa.gov	NASA-Ames
Peralta, Xomalin	xomalin@physics.ucsb.edu	iQUEST/UC Santa Barbara
Phillips, Thomas	phillips@submm.caltech.edu	Caltech

Name	E-mail Address	Affiliation
Piat, Michel	michel.piat@ias.fr	Institut d'Astrophysique Spatiale
Rabanus, David	rabanus@ph1.uni-koeln.de	University of Cologne
Richards, Paul	richards@physics.berkeley.edu	UC Berkeley
Rieke, George	grieke@as.arizona.edu	Steward Observatory/U of Arizona
Rosenthal, Dirk	rosenthal@mpe.mpg.de	Max-Planck, Garching
Ruhl, John	ruhl@physics.ucsb.edu	UCSB/Case Western Reserve University
Samoska, Lorene	lorene@merlin.jpl.nasa.gov	JPL
Samperi, S.A.	2_ssamperi@fair1.fairfield.edu	Fairfield University
Schwartz, William	bill@timeandcents.com	Fairfield University
Semenov, Alexei	Alexei.Semenov@dlr.de	DLR
Shafer, Rick	rick.shafer@gsfc.nasa.gov	NASA-Goddard
Sherwin, Mark	sherwin@physics.ucsb.edu	UCSB
Silverberg, Robert	Robert.Silverberg@gsfc.nasa.gov	LASP/NASA-Goddard
Skalare, Anders	anders.skalare@jpl.nasa.gov	JPL
Spieler, Helmuth	HGSpieler@LBL.gov	LBNL
Staguhn, Johannes	staguhn@gsfc.nasa.gov	NASA-Goddard
Stevenson, Thomas	thomass@pop500.gsfc.nasa.gov	NASA-Goddard
Sumner, Matthew	sumner@its.caltech.edu	Caltech
Vayonakis, Anastasios	avayona@submm.caltech.edu	Caltech
Walker, Christopher	cwalkew@as.arizona.edu	Univ. of Arizona
Watabe, Toyoki	watabe@u.phys.nagoya-u.ac.jp	Nagoya university
Wolf, Juergen	jwolf@mail.arc.nasa.gov	DLR - USRA/SOFIA
Young, Erick	eyoung@as.arizona.edu	University of Arizona
Zmuidzinas, Jonas	jonas@submm.caltech.edu	Caltech